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Teaching chemistry using guided discovery and an interactive computer tool.

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TEACHING CHEMISTRY USING GUIDED DISCOVERY AND AN INTERACTIVE COMPUTER TOOL

A Dissertation Presented

by

SAMIA A. KHAN

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Teacher Education and Curriculum Studies

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DEDICATION

In loving memory of my father, A.A. Khan.

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ABSTRACT

TEACHING CHEMISTRY USING GUIDED DISCOVERY AND AN INTERACTIVE COMPUTER TOOL

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An initial test of scientific inquiry skills revealed that students enrolled in a computer enhanced introductory college chemistry class using a guided discovery approach produced significantly larger gains after class instruction compared with two other introductory chemistry classes at the same institution and three introductory science classes at two other college institutions. The purpose of this study was to analyze the instructional strategy in this class to understand how it may have contributed to gains in inquiry skills. Classroom observations of the computer enhanced guided discovery class and two other lecture based chemistry classes, uncovered a pattern of instruction in the guided discovery case that was markedly different from the other two classes, yet more similar to model construction processes of scientists. The central pattern of instruction in the primary case was referred to as the guided discovery approach and was characterized by instructional strategies designed to

trigger generate, evaluate, and modify or GEM cycles, other teacher guidance strategies, and the integration of an interactive computer tool. Analysis of classroom observation data and student surveys confirmed a higher frequency of students' generating ideas about chemistry, constructing explanations, and quantitative problem solving in the guided discovery case than the lecture-based classes and a higher rate of teacher requests for students to engage in several of these processes. Small group observations revealed students' reasoning processes as they interacted with their teacher and the computer during instruction. Overall, compared with more traditional forms of chemistry instruction, the evidence suggests that the instructional strategies in the guided discovery case were successful in sustaining student engagement with several fundamental processes of scientific inquiry and may have led to the development of important inquiry skills. The guided discovery case used classroom activities that included finding trends, evaluating extreme cases, using incremental values, making comparisons, asking why, providing discrepant information, designing new tests, working back from the data, and thinking of an individual molecule, as several different strategies to foster inquiry. Rich descriptions of such instructional strategies may offer prescriptive methods for teachers to foster these processes in their classrooms and may represent a promising model for inquiry based instruction.

Keywords: chemistry, college, higher education, computer, inquiry, instruction, process, guided discovery, education

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CHAPTER 1

INTRODUCTION

1.1 The National Science Education Standards

Recent scores on international assessments have revealed deficits in science (Bracey, 2000) that persist into secondary school. At the k-12 level, national standards and state frameworks have responded by recommending teaching strategies that reflect our current understanding of conceptual change, metacognition, epistemology, child development, discourse and culture, and skill acquisition (Massachusetts Science & Technology Curriculum Framework, 1997; National Science Education Standards (NSES), NRC, 1996). In particular, one of their chief recommendations for teachers was that students must "arrive at the essential content of science and technology through *inquiry*" (Massachusetts Science & Technology Curriculum Framework, 1997).

According to the NSES (NRC, 1996), inquiry can be viewed, in part, as a strategy that uses knowledge claims and evidence to construct arguments and explanations. Compared to previous emphases, the NSES (NRC, 1996) has described inquiry according to different emphases, as shown in Table 1.

Table 1. Changing emphasis in the National Science Education Standards.

Less emphasis on	More emphasis on
separating knowledge with process	integrating all aspects of content
from covering many topics,	studying a few fundamental concepts
implementing inquiry as a set of processes	implementing inquiry as strategies, abilities, and ideas to be learned
process skills out of context	process skills in context
an emphasis on individual process skills such as observation or inference	multiple process skills such as manipulation, cognitive, procedural
getting an answer	using evidence and strategies for developing or revising an explanation
science as exploration and experimentation	science as argument and explanation

Less emphasis on	More emphasis on
doing few investigations in order to leave time to cover large amounts of content	more investigations in order to develop understanding, ability, values of inquiry and knowledge of science content
concluding inquiries with the result of an experiment	applying the results of experiments to scientific arguments and explanations
private communication of student ideas and conclusions to the teacher	public communication of student ideas and work to classmates

According to the NSES, engaging students in this this view of inquiry with the appropriate emphases may help students develop an understanding of scientific concepts and acquire the necessary skills to engage in scientific exploration.

Several of the processes currently associated with inquiry in science include: generating ideas; coordinating ideas with the evidence, evaluating the findings, weighing alternatives, constructing models that could be useful for making later predictions, and asking questions. While these processes certainly do not capture all of the cognitive, conceptual, procedural, social, and affective dimensions of scientific inquiry, it does provide an initial list of several processes that are currently associated with inquiry.

1.2 The problem

The Massachusetts Science & Technology Curriculum Framework for teachers has provided several images of inquiry. One of them is this brief scenario of inquiry in a 10th grade classroom in Massachusetts: a 10th grade biology teacher begins with the question: 'Why do leaves change color in the fall?' The first challenge for students in her class is to generate alternative explanations for leaf color change. They test and evaluate their hypotheses using paper chromatography, a method also utilized by botanists. Some of the questions students raise in the follow-up discussion are "why" questions. And to arrive at an explanation, the inquiry process begins again with another question. Finally, the teacher asks, 'how are broad leaved trees and evergreens adapted to seasonal changes?' Students question the evolution and adaptation of leaves. This is one of several images of inquiry that, according to the Massachusetts Science & Technology Curriculum Framework, holds promise for students' development of conceptual understanding and inquiry skills (adapted from Massachusetts Science & Technology Curriculum Framework for Life Science Domain, 1997, p.67).

Despite these recommendations and several examples of what inquiry could look like, the standards did not give specific prescriptive measures for how to conduct inquiry so that teachers could apply these recommendations to their local classroom situations. Consequently, there was a call for more prescriptive suggestions and rich descriptions of what the teacher could do in these classrooms (Keys & Bryan, 2001). Keys and Bryan (2001) suggested that practicing teachers offer perspectives on teaching and learning that were not available even from extended observational studies of and by researchers. Thus, they recommended that more research was needed on teacher-designed approaches to inquiry-based instruction, as well as teacher-designed adaptations of curriculum to their own unique situations. Keys and Bryan (2001) projected that research on the roles of teachers in implementing inquiry in the classroom would have a broad impact on science education because such studies would reflect what could be realistically accomplished in the classroom.

1.3 An opportunity

The opportunity, therefore, currently lies for researchers and educators to describe instructional practices and explicit guidance strategies that foster scientific inquiry and can be adapted to the science classroom. In pursuit of this goal, I initially designed a pilot study (Khan, 2000) that gathered evidence on classrooms at the college level that appeared to foster scientific inquiry as measured by a pre and post process test (the test is described in more detail in section 1.4.1 below). Case study analyses of the classrooms that produced pre and post course gains on this test could potentially produce elaborate descriptions of instructional practices in those classrooms for teachers who are interested in explicit strategies to foster scientific inquiry.

1.4 The research approach

The results of the initial pre-post process test are reported below, identifying a single classroom that emerged with positive pre-post course gains on the initial test. This classroom would be the focus of the case study.

1.4.1 An initial process test

In an effort to home in on those college science classrooms that may be effective at fostering inquiry processes in the classroom, an initial test was created and administered to several introductory science courses at three different university institutions in the upper Northeast US in 1999. There were 5 open-ended essay questions developed (Rea-Ramirez & Stillings, 2000), piloted, and administered in the test, two of which are relevant here.

The first question was designed to assess students' ability to generate hypotheses: "Two people are sitting in a room at equal distances from a bottle of perfume. After the bottle is opened, one person smells the perfume and the other person does not." The directions were to write a list of questions that occur to you about the statement, and based on one of these questions, write a well-formulated hypothesis that could actually be investigated.

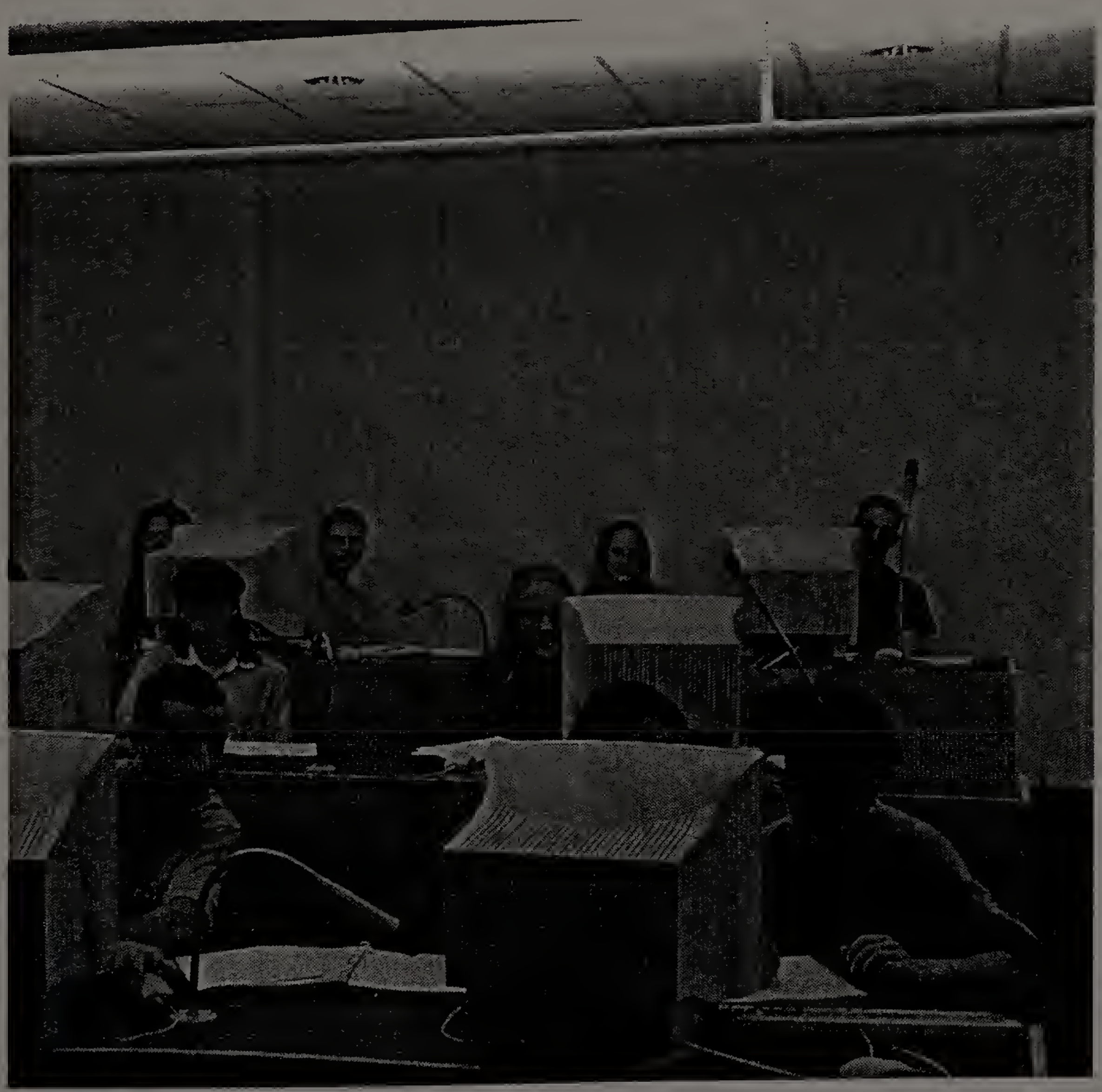
The second question was designed to gauge how students could describe data and analyze a relationship: "A farmer wanted to compare two corn varieties and their responses to varying amounts of water. She believed that Hybrid B would produce a better yield than Hybrid A, and she believed that daily watering would increase yields. She planted her north field with Hybrid A and her south field with Hybrid B. She watered one half of each field daily, while the other half of each field was watered once every four days." The data (in bushels per acre of corn) was displayed as a table and a graph. Students were asked to describe the data without drawing any conclusions, to evaluate the farmer's hypotheses that hybrid B would produce a better yield than hybrid A and that daily watering would improve yield, and to identify the assumptions the farmer made in the experiment, and to answer what further experiment might help to evaluate the two hybrids and the effects of watering. Both questions appeared on the pre and post tests.

The pre and post tests were collected (n=198 pre tests and 198 post tests) from all three university institutions, blinded, and scored with two coders who maintained an inter-rater reliability of 90%. We found that at the beginning of the semester, students from introductory science courses across the three institutions had similar scores on the pre-test (Rea-Ramirez & Stillings, 2000). But by the end of class instruction, only one class emerged with significant improvements on the test.

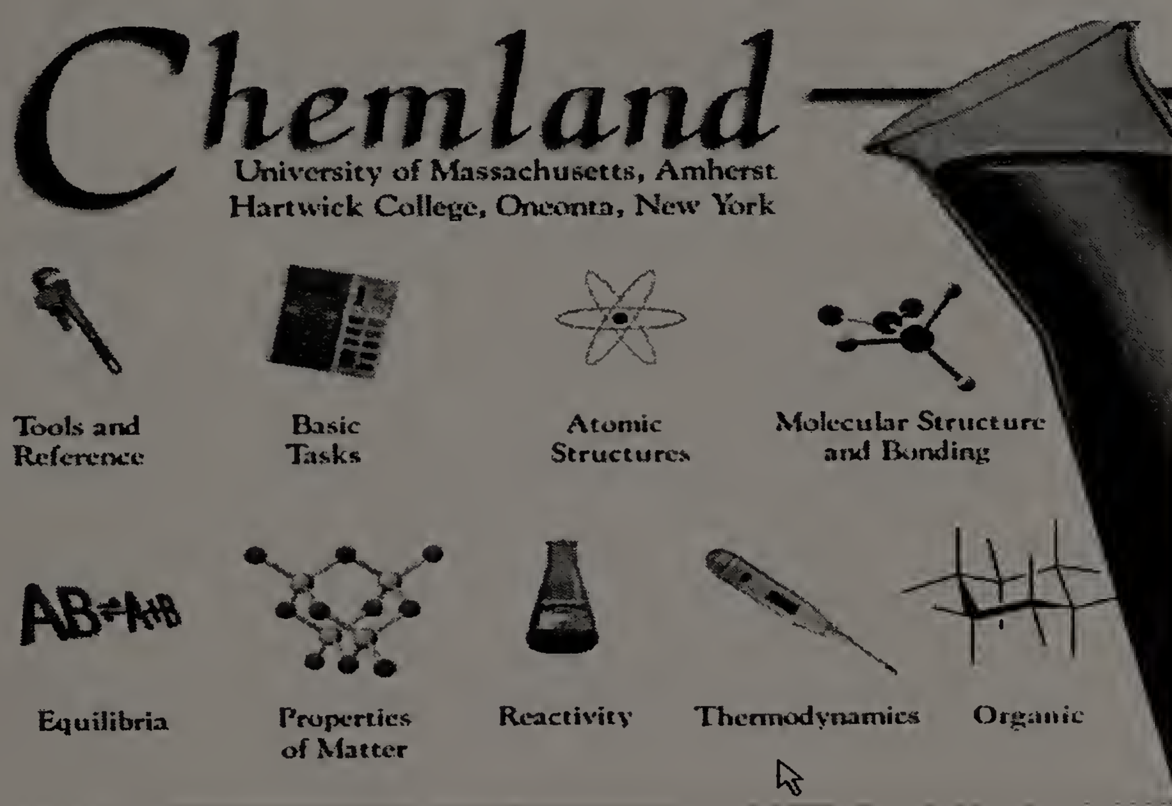
Students from an introductory chemistry class that used interactive computer tools performed significantly better on the test questions designed to measure the process skills of generating hypotheses, describing data, identifying assumptions behind conclusions, and designing experiments (positive pre-post differences $p<0.05$) than students who were taught chemistry in a more traditional way at the same institution (Rea-Ramirez & Stillings, 2000). These significant differences persisted across two additional institutions where students in introductory chemistry, biology, and natural science courses also took the test (Rea-Ramirez & Stillings, 2000) in 1999. Even though this was an initial test administered in 1999, a year prior to this study, these early findings suggested to us that there may have been factors in this class that contributed to the development of these process skills.

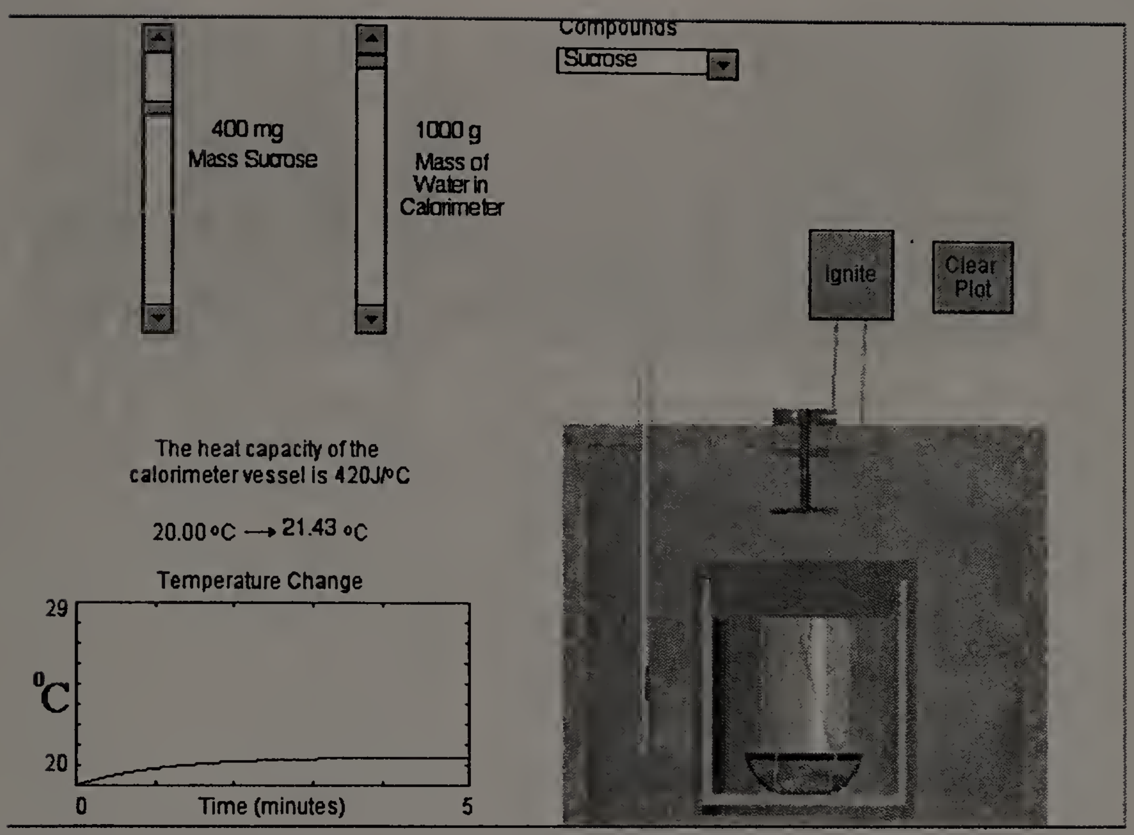
1.4.2 The case study

The focus of the current study was on this introductory chemistry class and the factors that may have fostered these processes. The chemistry department at this university became increasingly interested in innovations designed to improve students' understanding of relationships in chemistry through inquiry. One of the innovations introduced into several of their introductory chemistry classrooms was the integration of interactive computer tools.



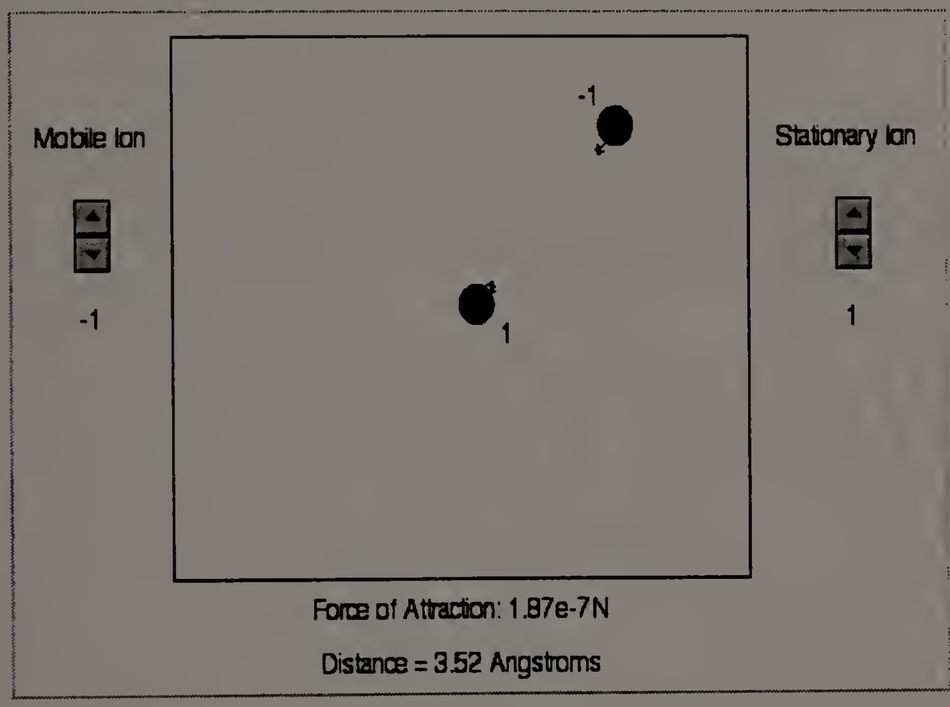
The electronic classroom had 26 computer terminals. Students were organized in pairs or groups of three at these terminals. Each terminal was equipped with software called Chemland (Vining, 2000). Chemland contained suites of multiple, compact, interactive computer modules that were computer representations of simulated lab experiments or molecular processes.



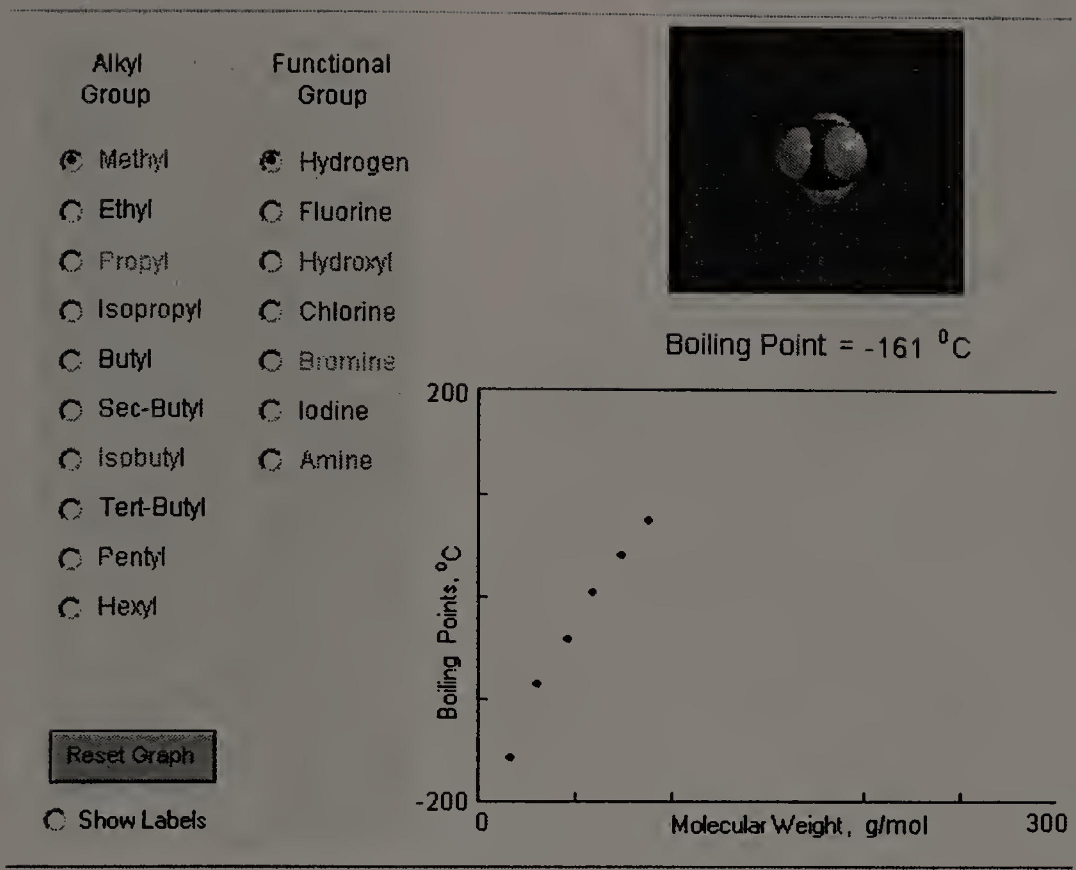


For example, in the computer representation above, students could interact with a representation of heat calorimetry. Students selected a particular mass and type of a compound to place in the calorimeter. That mass was shown to be inside an animation of the water bath in the calorimeter. Students could also select the amount of water in the water bath. The calorimeter was then ignited, and the increase in temperature was plotted as a function of time.

In another example, in the Coulomb's Law interactive tool below, students could change the distance and charge of the ions. They could change the distance of the ions by grabbing the mobile ion and dragging it farther or closer to the stationary ion. They could change the charge on both ions either to positive or negative or increase or decrease the same charge by using the up/down arrow keys. The arrows on the ions represented the force of attraction.



The arrows increased or decreased in size as distance or charge increased or decreased. A quantitative output of the force and distance was also displayed.



As the third example, in the organic boiling points interactive computer tool above, students selected an alkane or a functional group. The compound was then represented as an animation. As different alkyl or functional groups were selected, and the molecular weight of the compound changed, a graph of molecular weight versus boiling point was dynamically produced.

The suite of interactive computer tools that were integrated into this class were not intended to replace the laboratories, but rather represented the results of simulated lab experiments or the behavior of atoms of molecules under conditions not normally observable. Chemland was publicly available for teachers and students from other schools at the time of the study (Vining, 2000).

1.4.3 Chemistry Attitude Survey

Before the initial post test was completed, students were also asked to complete a student attitude survey known as the Chemistry Attitude (CAT) survey on a 5 point Likert response scale (Khan, 2000). One of the questions asked students in the initial course to rank where the greatest learning was happening out of nine choices[1]. Surveyed students from this classroom ranked peer discussion at the computer and discussion with their teacher as their top two learning factors out of 9 choices[1], whereas the lab and the text ranked last (two sections, n=56). At the very least, the initial test and initial CAT survey findings suggested to us that there was something interesting going on in this classroom, and that some of this interest was being generated around teacher and student interactions at a computer. Thus, it was the initial test that identified this classroom as one that produced gains in inquiry skills, and the initial CAT survey findings of this classroom that suggested that teacher-student interactions were valuable components of instruction according to surveyed students.

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[1] In the post Likert response survey, students were asked to "rank where the greatest learning was happening" for them among nine parts of the course:

1. Reading the text
2. Data collection on the simulation
3. Making up rules
4. Evaluating the rule
5. Finding out the rule needs to be changed because of new data
6. OWL
7. Laboratory
8. Class discussion with teacher
9. Peer discussion around the computer

1.5 Research questions

While there were a number of possible factors including the nature of the students, the physical setting of the classroom, and the computer software that may have influenced the improvement in process skills, one of the contributing factors to the gains may have also been the teacher's instructional approach. I seek to describe how the teacher's lessons and activity structures may have triggered student learning pathways that could have contributed to the development of students' process skills. With this kind of information, we may be able to gain some strategic insights to facilitate processes currently associated with inquiry in science classrooms.

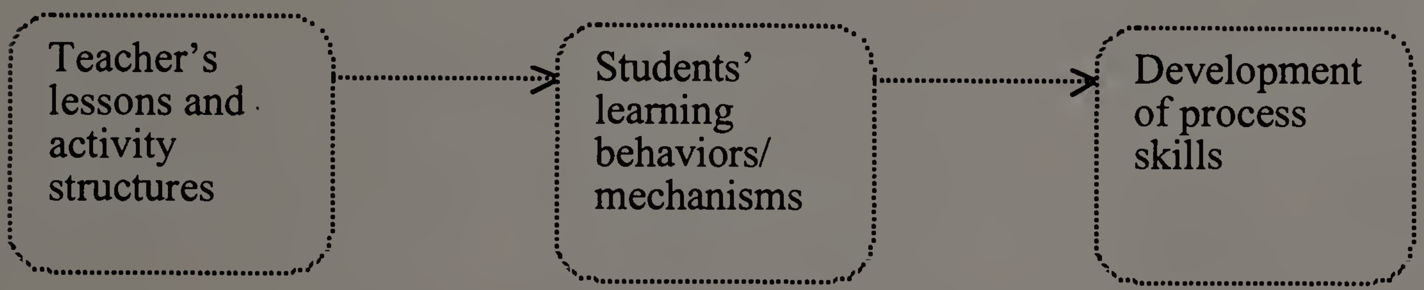

Figure 1. Theoretical mechanism to produce gains in process skills.

Figure 1. represents diagrammatically a theoretical mechanism that suggests that teacher activities trigger student learning, and student learning produces gains in process skills. By elucidating, elaborating, and reflecting on this mechanism, I seek to provide teachers with initial recommendations for a learning environment in chemistry that is designed to engage students in some of the fundamental processes currently associated with inquiry.

This case study focuses on three main research questions:

1. What are the instructional strategies and interactions in this class?
2. What are the major learning processes that are triggered during instruction?
3. How does the teacher's behavior support learning?

CHAPTER 2

LITERATURE REVIEW

2.1 Theoretical foundations

Research in science education was influenced by contributions from the field of cognitive psychology. Cognitive psychologists contributed several theories on how people learn (Piaget, 1952; Piaget, 1973; Vygotsky, 1978) and these theories inspired ideas and arguments on how people can learn science better (Driver, 1994; Metz, 2000; Brown, 1975; White, 2000; Chi et. al, 1994). Cognitive psychologists and educators who were interested in how students learn science developed several models of scientific thinking, some of which include scientific thinking as mental model construction (Clement, 1989) , logical thinking (Kuhn, 1988; Lawson et. al, 1991, 2000), and problem solving (Klahr & Dunbar, 1988). Mental model construction theory lays the foundation for how students of science could develop process skills (Clement, 1989) and transfer what they know to novel situations (Bransford & Stein, 1993; Bransford & Schwartz, 2002) in science. This theoretical framework supports the findings that emerged in the current study.

Clement (1989) interviewed advanced doctoral candidates and professors in technical fields to assess their approaches to unfamiliar problems. The interviewer asked these subjects to think aloud as they solved problems outside of their domain specialty. One question was, "You are given the task of rolling a heavy wheel up a hill. Does it take more, less, or the same amount of force to roll the wheel when you push at X, rather than Y?" The interviewer specifically asked subjects to give a scientific explanation for this situation without gathering new data. After analyzing the think aloud observations, Clement described the problem solving process of the subjects as hypothesis generation, evaluation, and modification leding to the formation and improvement of a mental model.

What is important about the creation of this model is that it appeared to be due to the construction and evaluation of a model rather than a series of inductions or deductions from prior principles, since the problem was new to the scientists, and they did not do any new experiments to gather data. Furthermore, there was no evidence from the interview that prior observations had been recalled in their problem solving process. Clement concluded that explanatory model construction of an unobservable process can be made via hypothesis generation, evaluation, and modification.

However, he also indicated that such a cycle may also have implications for developing process skills for students:

> [T]he most ambitious goal in science education is that of teaching scientific investigation or inquiry skills. In fact, it is extremely rare to find a class in which students are asked to propose and test scientific hypotheses for phenomenon.... Model criticism and modification processes would seem to be of crucial importance in the design of inquiry activities (Clement, 1989, p.377).

This foundational work on model criticism and modification also supports the work in this case study that focuses on inquiry skills and an extremely rare classroom that appeared to foster these skills.

2.2 Inquiry methods

In the National Science Education Standards overview, the National Research Council (NRC) presented a vision of a scientifically literate populace. To achieve this goal, the NRC stated that, "Inquiry is central to science learning" (NRC, 1996, p.2). Inquiry; however, is a term that can mean different things to different people, and can be interpreted in multiple ways. Rather than attempt to construct one definition that could be applied to all classrooms, researchers and educators have attempted to describe what inquiry looks like in research laboratories (Dunbar, 1994), in computer-enhanced environments (Barowy & Roberts, 1999; Soloway et. al, 1997), and in the classroom (Rosebury et. al, 1992; Roth, 1993; Hammer, 1995; Samarapungaven, 1992). Some of these descriptions were in contrast to traditional learning environments and hands on learning environments. Using these descriptions generated by researchers, the National Research Council characterized inquiry as students actively developing their understanding by combining scientific knowledge with reasoning and thinking skills. The active methods they described included students asking questions, constructing explanations, testing those explanations against current scientific knowledge, and communicating their ideas to others. Several of the inquiry methods identified in the NSES (NRC, 1996) were similar to the model construction processes of scientists that were identified by Clement (1989). Thus, the model construction processes identified by Clement may provide a framework for achieving several of the inquiry goals described in the NSES (NRC, 1996).

2.3 Computer technologies for the classroom

Computers have become increasingly important to scientists in laboratory measurement, data collection and analysis, modeling, database searches and communication to the broader scientific community. In addition, computers have become increasingly prevalent in our classrooms (Becker and Ronnkvist, 1999). With the recent influx of interactive computer tools; however, there was some initial hope that these computer tools could help us to meet our inquiry goals in chemistry in much the same way that they support scientists. The literature review that follows is a survey of the research on computer tools and instructional supports designed to facilitate inquiry processes.

2.3.1 Classification of computer technologies

There are a variety of powerful and subtle computer technologies available to educators to work within their classrooms. For example, computer technologies are available to construct complex molecular models (Hyperchem, CrystalDesigner, RasMol), input data or information and rapidly represent it (EQS4Win, WEBGEN, HASL), animate and display unobservable processes (Chemland), search large databases (Malathion), represent the results of simulated lab experiments (Chemland), or communicate with peers and experts (online chemistry and science communities, discussion groups, and bulletin boards), to name a few. Thus, for the science teacher, there are a number of positive reasons to integrate interactive computer tools into the science classroom.

Jonassen (1998) attempted to categorize the vast array of educational technologies available to science teachers according to their cognitive contributions or affordances. These categories included:

1. Semantic organization tools (databases, semantic networks) for organizing what students know.
2. Dynamic modeling tools for building simulations and representing mental models (expert systems).
3. Synchronous and asynchronous conferencing environments for socially co-constructing meaning.
4. Knowledge construction environments (hypermedia, multimedia, web publishing).
5. Information interpretation tools (interactive visualizations, information search engines) for better understanding information encountered.
6. Video for visualizing a range of ideas that students can generate.

In an adaptation of Jonassen's categories of computer applications, a classification scheme of computer tools available to science educators was suggested below:

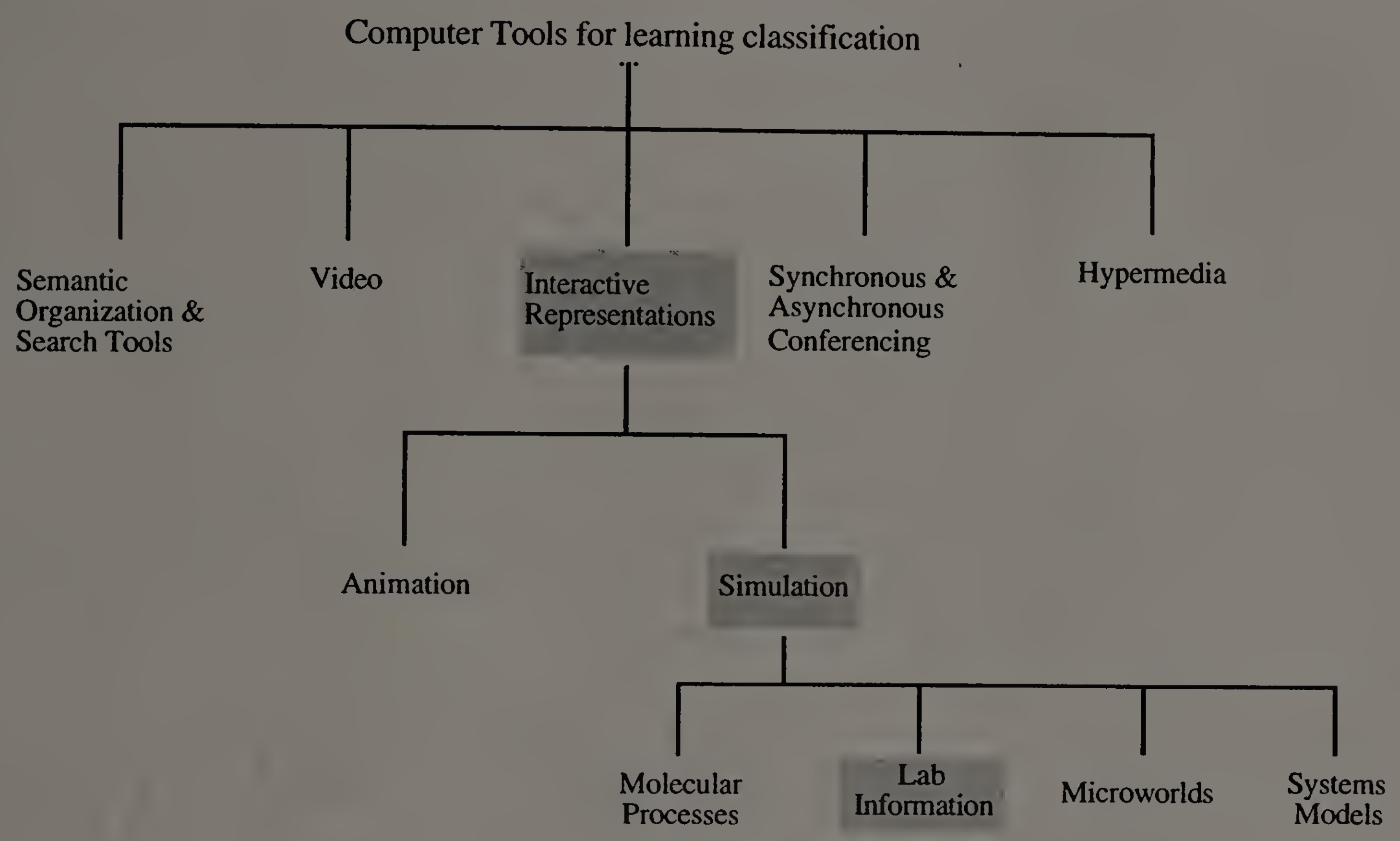

Figure 2. Computer tools for learning classification scheme

2.3.2 Instructional simulations

The current study focused on educational technologies that could be classified as instructional simulations or more specifically, interactive computer representations that were simulated macromolecular processes (as opposed to molecular processes). In this case study, the majority of interactive computer representations were simulated macromolecular processes or lab results (see the highlighted box in Figure 2). For the purposes of this study, a simulation was referred to as a program that allowed the user to interact with a computer representation of a scientific model of the natural or physical world or a theoretical system or environment. Instructional simulations are those simulations that are designed to function within a learning environment (Thomas & Hooper, 1991; de Jong, 1991). The learning environment may have had multiple learning goals ranging from learning about procedures such as airplane repairs (Lajoie & Lesgold, 1992) or lifesaving measures in medical emergencies (Eliot & Woolf, 1994), to processes such as generating testable relationships about error in chemistry titration experiments (van Joolingen & de Jong, 1991), or conceptual understanding; such as understanding the difference between heat and temperature in thermodynamics (Lewis, et al., 1993). Thus, instructional simulations could be designed to support multiple learning goals such as learning procedures, learning content, or learning processes.

Instructional simulations could be confused with computer modeling or microworlds that function in an instructional capacity. There are subtle differences between the three. In computer modeling, the learner not only could manipulate variables in the simulation, but the learner could also add, delete, or modify the variables and parameters in the program or the relations between them. Thus, computer modeling allows the user to see "inside the glass box" and build a runnable model rather than manipulate an existing one. In some sense, users could manipulate the program that runs a simulation.

Microworlds, on the other hand, are highly complex simulations that enable users to explore a particular problem area by inventing their own activities and experiments in a realistic setting. Although learners have additional tools such as expert feedback and databases at their disposal, the setting intentionally bears close resemblance to reality in order to avoid interference with a natural learning process (di Sessa, 1987). Consequently, learners are encouraged to engage in a self-regulated exploration process by which major principles of the microworld remain to be discovered (Bruner, 1976) until instructional interventions interrupt and interfere with this process of discovery learning.

Microworlds of lab experiments allow the user greater control over the experimental design and set up. For example, microworlds of lab experiments allow the user to "hand pick" the glassware for the lab experiment. Thus, as educational technologies, simulations have subtle differences from computer modeling and microworlds. For the purposes of this study, instructional simulations were considered as interactive computer representations or tools that could be manipulated for the purpose of learning and functioned in a learning environment.

2.4 Survey of instructional strategies associated with computer tools

Interactive computer tools could be engaging for chemistry students because they could manipulate variables in multiple ways and observe the changes. Because of this kind of interaction, there was some initial promise that chemistry students could learn to solve problems by testing their ideas using such interactive computer tools. Previous literature showed, however, that the use of interactive computer tools designed to facilitate inquiry in science had variable effects on the development of inquiry skills (Vasu & Tyler, 1997) such as being able to generate hypotheses, as described in a review of simulation studies (de Jong, & van Joolingen, 1998); interpret data and evaluate arguments, as described in a study of a series of simulations that presented data about the interaction between predators and their prey (Rivers & Vockell, 1987), and make predictions, as described in a study of a thermodynamics simulation that incorporated prediction-making using graphs (Lewis, et al., 1993). Studies also reported that the use of interactive computer tools in the classroom improved motivation, enhanced the cognitive learning of factual information, processes, and critical thinking skills; improved transfer of learning to other situations, and students' attitudes towards the subject (de Jong, 1991). But according to some experts, interactive computer tools do not, simply by their own nature, "invite" students to exhibit processes such as hypothesis generation, prediction, or data interpretation (Njoo & de Jong, 1991; Jonassen, 1994). Rather, some researchers have turned their attention to the instructional aids or supports associated with the use of interactive computer tools to develop these skills.

The instructional supports associated with interactive computer tools have ranged from highlighting main points such as those found in paper and pencil fill in forms (Njoo & de Jong, 1991) or in assessment rubrics designed to promote reflective practices (White and Frederiksen,1998); model progression (Quinn & Alessi,1994; de Jong, et al.,1999); sequencing assignments such as those that ask students to predict the relation between two variables first (Swaak et.al, 1998; Lewis et al., 1993), or coaching with programmed hints or feedback (Lajoie & Lesgold,1992; Rivers and Vockell, 1987; Rieber et al.,1996; Veenman & Elshout, 1995; Rieber & Parmley, 1995). It appeared, however, that even the use of very complex interactive computer tools and these different types of supports have not always been sufficient to help students develop conceptual understanding or process skills (Njoo & de Jong, 1991; Quinn & Alessi, 1994; van Joolingen & de Jong, 1991, Simmons & Lunetta, 1993; Shute & Glaser, 1990, Lavoie & Good, 1988). A more detailed description of these supports is presented below.

2.4.1 Hypothesis generation with computer tools

The instructional practices that have been associated with inquiry-based computer tools have focused on the processes hypothesis generation, prediction making, experimental design and planning, and interpretation. Those studies investigating hypothesis generation in conjunction with the use of interactive computer tools have used a range of descriptions to define the term hypothesis. Hypotheses have been referred to as simple relationships that are testable, educated guesses, rules or predictions, or relationships accompanied with an explanation. For the purposes of this study, a conceptual hypothesis was referred to as a relationship that is testable by rational means and accompanied by an explanation. An experimental hypothesis was referred to as a relationship that is testable by experimentation and accompanied by an explanation. A prediction and a rule, however, was referred to as a relationship that may or may not be testable and need not be accompanied by an explanation. Not all studies on hypothesis generation using simulations used the term hypothesis this same way (quite often, hypothesis was used to refer to a relationship between two or more variables that could be tested on the simulation). For the purposes of this study, however, an hypothesis was reserved for a relationship that could be tested empirically or rationally with some explanatory power.

In computer representations that have reportedly been designed to facilitate the construction of testable relationships in a scientific domain, the instructional practices that have been associated with the computer tool have included paper and pencil fill in forms containing headers such as variables, hypothesis, experiment, prediction, data interpretation, and conclusion (Njoo & de Jong, 1991). In this study, the goal of instruction was to promote discovery learning by providing forms with the hypothesis cell filled in for a group of mechanical engineering students. The "hypotheses" in the cells included, "with a proportional control law you do not have influence on the stability of the system", or "the value of the feedback amplification K has influence on the sub or super critical damping of the system." The group with the "hypothesis" filled in on the forms was able to generate the correct conclusions more frequently than groups who were not provided with a sample "hypothesis" (Njoo & de Jong, 1991).

Learners, especially those that are new to a domain, may encounter difficulty generating hypotheses or constructing testable relationships from an interactive computer tool (Njoo & de Jong, 1993). Positive findings were reported using fill in forms, but in this case, the instructor provided the relationship to be investigated (Njoo

& de Jong, 1993). Using hypothesis scratchpads, however, van Joolingen and de Jong (1991) attempted to support the learner's construction of testable relationships [2] about chemistry titrations without actually providing the relationship.

In order to facilitate the construction of "testable relationships", the hypothesis scratchpads offered only the elements needed to build the relationship such as variables and relationships in pull down menus. [3] For example, three menus were available to some of the users including a variables selection table, a condition selection table, and a relation selection table. When developing a testable relationship about errors in titration experiments, learners could select "the error of a quantity that takes part in a calculation of another quantity" as one variable, and "If…becomes greater than…" as a condition or "if ….increases then….also increases" as a relation variable. Compared to the control group that did not use hypothesis scratchpads while using the chemistry titration simulation, students in the "hypothesis scratchpad" group used a larger number of different variables and generated a higher number of testable relationships with two variables with some relation (albeit imprecise). This implied to the authors that the

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[2] The term "hypothesis" in their study was described by the authors as a relationship between variables: "An hypothesis about a simulation model is a statement that a certain generic relation holds between two or more conceptual variables, where a generic relation is a generalization of the traditional relation concept, allowing for fuzzy and incomplete descriptions of a certain relationship. A conceptual variable is a generalization of the variables present in the computer simulation and a generic relation" (Njoo & de Jong, 1993),p. 391). The generation of "hypotheses" was assumed to occur as a dual search in an hypothesis space and an experimental space (Klahr & Dunbar, 1988). According to this theory, the hypothesis space contains all the possible hypotheses about the system under study, and the experiment space contains all of the experiments that could be carried out within the system. The authors predicted that some students would develop a correct "hypothesis" only after they have performed titrations and ruled out other possible rival hypotheses; while others would perform titrations only after an "hypothesis" had been articulated at the outset. It appeared hypothesis in this study was also tied to the expectation of experimentation, and thus, the definition could be redescribed as the construction of a "testable relationship."

[3] The use of pull down menus to stimulate the generation of testable relationships in simulations is not new. In Smithtown (Shute and Glaser, 1990), a simulation of microeconomics, learners had an "hypothesis menu" which offered a structured framework for creating testable relationships. The menus consisted of an objects (or variable) and verbs (or conditions) menu which helped users create testable relationships like "as price increases, then quantity demanded decreases." Such relationship building menus continue to be used in current modeling software to facilitate scientific inquiry such as the relationship maker in Model-It (Soloway, et al., 1997).

structured scratchpad had potential to stimulate "theorist" behavior, but it was clear to them that more work was needed by students to develop precise, correlational relationships for their "hypotheses" (van Joolingen & de Jong, 1991).

In a second example, Quinn & Alessi (1994) studied the interaction between the construction of testable relationships and the complexity of a simulation. In this study using a simulation of a flu epidemic, students were told to write an hypothesis that would minimize the number of sick people, using two out of four variables available on the simulation. One group of students generated a single testable relationship while another group of students was told to generate multiple relationships to test. According to the authors, the presumed advantages of approaching experimentation with multiple "hypotheses" included a greater likelihood of generating the correct hypothesis and the efficient use of information to eliminate several incorrect hypotheses simultaneously rather than eliminating individual hypotheses sequentially. Both groups of students ran their tests on the simulation, progressing from two variables, to three and then four (model progression). After each run, the students were required to indicate their conclusions regarding the set of values most likely to minimize the number of ill people. They were given feedback before being asked about what combination of three variables would minimize the number of sick people. The authors found that the multiple hypotheses strategy did indeed lead to a greater proportion of students who came to the correct conclusion in each phase of the experiment but only if the complexity of the simulation was low. At higher levels of complexity in the simulationno advantage of the multiple hypotheses strategy over the single hypothesis strategy could be found.

Slack and Stewart (1990) used the Genetics Construction Kit (GCK), a realistic simulation of fruit fly crosses to study 30 high school students' ability to generate testable relationships about genetics. According to the authors, the advantage of using GCK was that the simulation significantly increased the amount of research students could do compared with the time required to cross fruit flies in the lab and observe several generations of offspring. Each simulation problem began with a population of field-collected organisms. The sex and phenotype of each individual was also identified. Once the field collection was displayed, students could select individuals to be the parents for their crosses. Generations of offspring could be produced until the student was ready to explain the phenotype data in terms of inheritance. According to the authors, solving these problems required students to reason from effects (phenotype data) to causes (underlying genetics mechanisms), making them different from algorithmic kinds of problems in genetics. Data was collected in the form of think aloud interviews and computer generated information on students' crosses. After analyzing the data, the authors reported that students generally followed three problem solving strategies to generate their tests: an unplanned approach (lack of a testable relationship), a working backward approach (explaining rather than predicting) and an approach emphasizing counting and ratios. These observations led them to believe that students generally lacked "hypothesis" generation strategies.

Slack and Stewart (1990) concluded that computer simulations, including those that provide a realistic problem solving environment, were still not sufficient to elicit process skills because the simulation did not help students develop connections between conceptual knowledge and problem solving strategies. They recommended explicitly teaching hypothesis generation and testing strategies and presenting genetics concepts and principles so that the relationships were more obvious to students..

It appeared that even the use of very complex simulations and their instructional supports such as hypothesis fill-in worksheets (Njoo & de Jong, 1991), hypothesis scratchpads and menus (van Joolingen & de Jong, 1991), model progression (Quinn & Alessi, 1994), or realistic contexts (Slack & Stewart, 1990) have met with variable success. It appears that the use of these menus, model progression, and realistic contexts within computer tools were not always sufficient to help students generate clear, testable relationships or hypotheses with explanatory power. This difficulty may have been compounded when students were asked to construct relationships about processes that were unobservable and unfamiliar to them.

2.4.2 Controlling variables with computer tools

In order to simplify complex scientific inquiries that have multiple variables, some interactive computer tools have offered model progression as a way to help students control variables and design experiments. In model progression, the model was introduced gradually, step by step. Swaak et al. (1998) used a simulation on harmonic oscillation that proceeded from free oscillation, through damped oscillation, to oscillation with an external force to determine the effect of model progression on intuitive knowledge (insight into the domain). The number and kinds of input variables that could be controlled and the output variables that could be observed increased with each level. The authors suggested that the use of model progression may help learners discern relevant variables (Swaak, et.al, 1998). They found at the conclusion of their experiment that model progression improved students' intuitive knowledge about oscillations. In the physics domain of collisions, however, model progression was found to have no effect on intuitive knowledge (de Jong, et al.,1999), and likewise, in a simulation of a flu epidemic, Quinn and Alessi (1994) found that progressing from two variables to three, and then four variables had no overall positive effect on performance.

Hints, coaching and tutoring have also been explored as a means of instructional support for the development of an experimental design using interactive computer tools. Strategic hints were generally applicable strategies presented to the learner to help them solve problems. For example, strategic hints such as, "It is a good idea to change only one variable at a time, and look for patterns or relationships" were presented to high school biology students in Rivers and Vockell's (1987) predator-prey simulation, Balance. In addition, specific hints about the relationships were also presented: "the denser the vegetation in the environment, the easier it is for the wolves to capture the deer." Using the hints, one group of high school students was told to conduct a planned experiment, analyze their data and draw conclusions. A second group did not receive these hints before using Balance. Students in a third group did not use Balance at all but followed a traditional laboratory exercise without the use of computers. Approximately the same amount of time was spent on the topic for the control group as the treatment groups. All students in the groups completed a pre-post Watson-Glaser test of critical thinking as a measure of their ability to make inferences, recognize assumptions, deduce conclusions, decide whether or not conclusions were warranted, and evaluate the strength of arguments. The results of the tests showed that the students who received the hints outperformed the two comparison groups on the test of critical thinking. Thus, instructional strategies associated with the use of interactive computer tools to help control variables or design experiments included model progression and the use of hints. Model progression designed to support controlling variables has met with variable success in the two studies presented; whereas providing strategic hints met with some apparent success at controlling variables.

2.4.3 Evaluating and modifying ideas with computer tools

Scientific inquiry is a process that includes, as one part, the evaluation of hypotheses and ideas. The evaluation of ideas with interactive computer tools have been reported in several studies. In all cases, the computer tool presented information that was apparently anomalous. In the case of Smithtown (Shute & Glaser, 1990), those students with a better causal model of microeconomics used an analogy to try to account for disconfirming evidence. They persisted (Schauble et al, 1991) and were successful in modifying their ideas about economics. Hafner and Stewart (1995) showed that high school students could modify models of genetics when presented with anomalies in a computer simulation.

Gorsky and Finegold (1992) conducted a study of nine students in grades 9-12 and their responses to anomalies presented in a physics simulation. The simulation prompted each student to state his or her perception of force acting in each system. It presented the system as if the student's own force model were true and compared it with the ideal model. Gorsky and Finegold observed that when modifications of existing schemata were minor, students tended to resolve anomalies through independent thought. When major modifications were required, however, students often referred back to the simulation for more information. Thus, students were presented with information that they had to recognize was anomalous and then resolve the discrepancy. In both cases, the authors seemed to suggest that student persistence and independent thought helped them to evaluate and modify their ideas.

2.5 Summary of computer tools for learning

Computer simulations can be both powerful or subtle technological tools for chemistry teachers to use in their classrooms because they can provide tools for constructing complex molecular models, dynamically represent information in multiple ways, animate unobservable processes, search within large databases, or communicate with experts, to name a few. Thus, for the science teacher interested in inquiry, there are a number of positive reasons to integrate interactive computer tools into the science classroom.

But according to some researchers (Njoo & de Jong, 1991; Jonassen et al., 1994), interactive computer tools do not necessarily, simply by their own nature, "invite" students to exhibit some of the fundamental cognitive processes associated with inquiry such as hypothesis generation, prediction, or data interpretation. Rather, some researchers have turned their attention to the kinds of instructional support associated with the use of these computer tools. But after experimenting with a significant range of instructional support measures such as assignments, scratchpads, and model progression, it still appeared that some processes such as generating hypotheses and evaluating them remained difficult for many students despite these instructional support measures. Thus, something else was needed to facilitate these processes in a computer enhanced classroom (Stratford, 1997).

Initial recommendations were produced that suggested interactive computer tools be integrated into a larger inquiry cycle (Lindstrom et al., 1993) and used consistently; that at least one of the modes of use involve group discussion and sharing (White, 1993; Scardamalia et al., 1994); and that teachers remain actively involved in the process by scaffolding student questions, structuring complex activities (Quinn & Pena, 1996) and guiding hypothesis generation and evaluation. While these recommendations may appear simplistic, the studies presented here have reminded us that there is a need to re-evaluate how we are structuring inquiry activities with interactive computer tools to reach our learning goals.

2.6 Designs of computer-enhanced learning environments

Many of these recommendations went largely unheralded until the advent of more contemporary work that appears to have shifted from "designing better educational technologies with instructional aids" to include a more careful consideration of the design of the entire learning environment to facilitate goals and meet standards. This shift means a careful consideration of the learning goals that form the foundation of structured activities and activity sequences with interactive computer tools. Unlike the work that has been reported on previous software, new models of designs of learning environments that fully integrate carefully thought out activities with interactive computer tools and classroom resources are emerging. Some of these computer-enhanced designs of learning environments are described below.

2.6.1 Physics with Thinkertools

Learning goals. In an effort to encourage reflection, White and Frederiksen (2000) designed a learning environment that attempted to develop students' metacognitive knowledge through scaffolded inquiry, reflection, and generalization. The learning environment they developed promoted reflection through thoughtful questioning and assessment at each phase of the inquiry cycle.

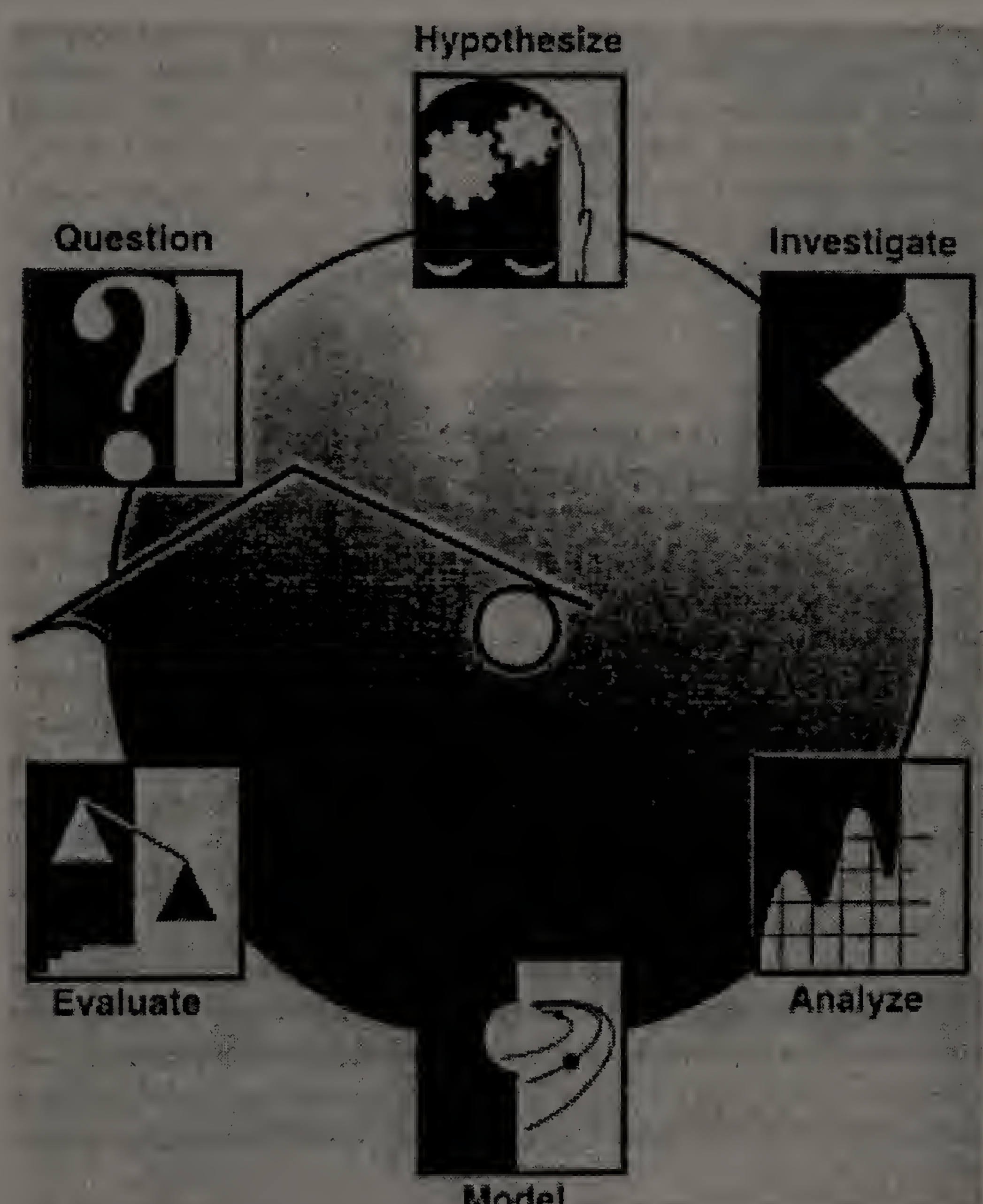


FIG. 11.4 A model of the scientific inquiry process, which is presented to students as a sequence of high-level goals to be pursued.

Thoughtful questioning and assessment were the chief learning strategies designed to facilitate the development of metacognitive knowledge in this physics learning environment. In a controlled comparison, White and Frederiksen (1998) found that facilitating metacognitive processes may have contributed to students' learning on a test where students were asked to investigate a research question, create competing hypothesis, design an experiment, make up results, analyze their made up data to research a conclusion and relate this conclusion back to their original competing hypothesis. The improvement in these process measures on the test was especially notable for traditionally low achieving students.

The software. Students could interact with Newtonian models of force and motion by changing the elastic properties of objects in Thinkertools computer software. According to the authors, with Thinkertools, students defined and changed the properties of any object such as the mass of the object and velocity, turned friction and gravity on or off, placed barriers on the screen, and selected different friction laws. In addition, Thinkertools presented students with an array of measurement tools, graphical representations, and analytic tools. As the object moved, it left behind dotprints that showed how far it moved in each second and thrustprints that showed when an impulse was applied. There was also a datacross that showed x and y velocity components. The students could also pause the simulation and proceed in time step by step with Thinkertools. The screen shot on the next page (found in Jacobsen & Kozma, 2000) shows Thinkertools force and motion software (White & Frederiksen, 2000).

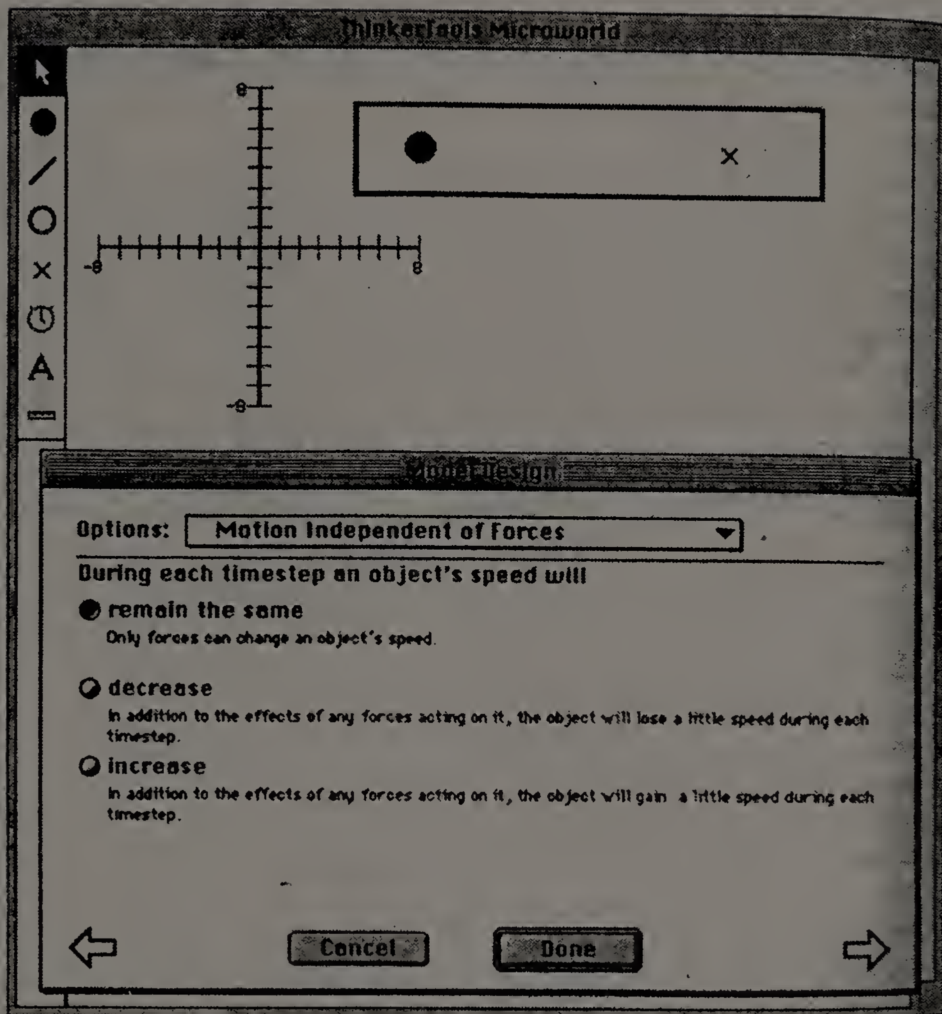


FIG. 11.12 An example of the model design feature of the ThinkerTools force and motion software.

Students could create and experiment with different models with Thinkertools. The authors hoped that this dynamic interaction with the software could encourage a transition from students' intuitive ways of reasoning about the world to a more abstract representation of the behavior of a system.

Physics with Thinkertools. The design of the learning (White & Frederiksen, 2000) environment in physics integrated the use of a computer tool called Thinkertools, and was organized around an instructional framework composed of a series of investigations of physical phenomena that increased in complexity. For each new topic in the curriculum, students followed an inquiry cycle that began with developing a research question[4], and generating predictions and theories about what might happen in some specific situations (thought experiments).

After presenting their predictions to the class, students broke into research groups to design and carry out experiments with Thinkertools and real-world experimental materials. After the students completed their experiments, they analyzed their data to see whether there were any patterns. The student groups tried to summarize and explain their findings by formulating a law and a causal model to characterize their conclusions. Students prepared posters of their laws and did oral presentations. They evaluated, as a whole class, the findings from all the research groups and chose the best laws and models that explained their data. Once the class chose the best laws, students tried to apply them to different real-world situations and investigated how useful their models were for predicting and explaining what would happen. They also investigated the limits of their models,raising new research questions according to White & Frederiksen (2000) and bringing the class back to the beginning of the inquiry cycle.

The first pass through the inquiry cycle that consisted of question, predict, experiment, model, apply and question again involved scaffolding where students were given experiments to do and the laws before they had to create their own; in the second pass through the inquiry cycle students were given experiments to do but they had to construct the laws themselves, and in the third pass through the inquiry cycle, students designed their own experiments and constructed their own laws to characterize their findings. By the end of the curriculum, students were carrying out independent inquiry on a topic of their own choosing. Throughout this process, students monitored their progress in each phase of the inquiry cycle by evaluating their work and others from a set

[4] On the first day, students toss a hacky sack around the room while the teacher has them observe and list all of the factors that may be involved in determining its motion. As a strategy, the teacher suggests the need to simplify the situation, and this discussion leds to the idea of looking at simpler cases, such as that of one dimensional motion where there is no friction, to the case with friction, and then with gravity. At the end of the curriculum, students are presented with a variety of possible research questions to pursue and they carry out research of their own choosing

of criteria for judging research. They gave one another feedback both verbally and in writing.

The instructional simulation may have contributed to the learning environment in physics because students were able interact with artificial scenarios with Thinkertools (White& Frederiksen,2000). Students were able to change the mass of the object and velocity, to turn friction and gravity on and off, and to select different friction laws with Thinkertools. In this way, according to White & Frederiksen (2000), students could "dramatically alter the parameters of the simulation and to look at extreme cases, which are hard to utilize in real inquiry." In addition, Thinkertools included measurement capabilities, graphical representations, and analytic tools. Students could pause the simulation and to proceed time step by step with the analytic tools. The authors hoped that this dynamic interaction with the simulation could provide a transition from students' intuitive ways of reasoning about the world to the more abstract methods that scientists use for representing and reasoning about the behavior of a physical system (White & Frederiksen, 2000).

The design of this physics learning environment with Thinkertools appeared to engage students in generating research questions about physics, making predictions, designing experiments, analyzing and evaluating data, constructing explanatory, causal models, reflecting on the process of investigations, and communicating their ideas with others. The learning environment was also embedded with active strategies for learning (reflective assessments, real-world experiments, poster presentations and collaboration), and the integration of interactive computer representations (Thinkertools). The students in this learning environment produced significant improvements after this instruction on tests measuring inquiry skills.

2.6.2 Genetics with the Genetics Construction Kit

Learning goals. The learning goal of this learning environment was to encourage students to solve problems in genetics using what they already know (Hafner & Stewart, 1995).

The software. Hafner & Stewart (1995) examined the use of anomalies using the Genetics Construction Kit (GCK) computer tool to achieve this learning goal. The GCK software attempted to provide realistic practice with the tools and problems of classical genetics. The simulation consisted of a student laboratory and a construction kit for designing a population of organisms for study. Students could carry out fruit fly crosses by selecting individuals to be parents, performing crosses between them, and observing the traits and variations of the resulting offspring.

Genetics with GCK. The first 5 weeks of an elective high school course on genetics was devoted to studying Mendelian genetics. At this time, students were encouraged to think in terms of models. Instruction began with descriptions of "modeling" and a "black box" activity where students made inferences about the causal mechanisms of an unknown "system" hidden inside a box. Students next read portions of a translation of Mendel's work and received a visit from an actor portraying "Gregor Mendel" who described the problem he was dealing with as well as his explanatory model. In that context, a model of simple dominance was developed. Students were then introduced to a simple dominance genetics model and a meiotic genetics model. Then, they practiced 1 and 2 trait simple dominance problems using the GCK simulation. Following student practice, a model of the process of meiosis was then developed by the instructor. Students used the meiotic model to solve 1 and 2 trait simple dominance problems with the GCK simulation. Students were subsequently presented with codominance problems where the data did not fit the simple dominance model. They used this model to recognize anomalies, and they revised it to accommodate the new data. Student research groups presented their new models and engaged in critique and persuasion regarding their viability of their models. Successive rounds of this model-revising problem solving in genetics (MRPSG) cycle were repeated to solve more complex gene interaction and autosomal linkage problems with GCK software.

A group of 6 students were selected from the class following the 1st round of model-revising problem solving. They were selected based on their ability to use the simple dominance and meiotic models successfully and their ability to participate outside of class. During their free periods, the students attempted to solve the same problems on the simulation as those scheduled for the classroom. The students received one practice period "thinking aloud" before they solved five additional problems.

The think aloud transcripts were then examined for general and domain-specific heuristics employed as students were engaged in MRSPG. Heuristics were identified. According to Hafner & Stewart (1995), the identification of the spontaneous heuristics associated with model-revising problem solving was a recursive process for them: heuristics were first identified for the first problem and then used as a framework for the second problem. If new heuristics were identified in the second problem, then the first problem was reassessed to whether or not those heuristics were evident. This recursive process was continued for the remaining sequence of problem types, until students' heuristics in MRSPG were identified.

Hafner and Stewart (1995) employed a model-revising-in problem-solving-in-genetics (MRPSG) framework to analyze students' heuristics. Model space search in MRPSG was similar to the dual space search process between an hypothesis space of rules and an experimental space of instances described in Klahr & Dunbar's (1988) SDDS theory of scientific reasoning. In MRSPG, however, the search was conceived as being through a space of the number of genetic crosses performed and another space that represented the processes associated with the formulation and evaluation of genetic theories.

They found that three general heuristics emerged that were used by students in order to construct their model: search the model space, test the model, and evaluate the model. Searching the model space began with evoking a prior model from memory in response to an earlier cross that they may have done. The student extracted information from the cross search space that conformed and did not conform (anomaly recognition) to the expectations of their model. The student postulated causal factors for the perceived differences in the models in order to revise a model. Finally, the model was evaluated with respect to both its explanatory and predictive sufficiency using the simulation. The revised model could then have been accepted or used as a template to engage in another model-revising cycle. Hafner and Stewart (1995) highlighted their observation that as students searched the cross space, they employed a general heuristic of using "existing models as 'templates' to recognize anomalies and propose the existence of causal factors responsible for the anomalies". Seventy percent of attempts using this approach with GCK resulted in successful solutions of complex genetics problems. Thus, the overall design of this genetics learning environment included model construction and model revision, strategies for learning (black box modeling activities, discrepant information), and the integration of an interactive genetics computer simulation (GCK). According to the authors, the majority of students in this learning environment produced successful solutions to solving genetics problems (Hafner and Stewart, 1995).

2.6.3 Air pollution with Tool-Soup, Model It, and e-Chem

Learning goals. The goal of this learning environment was to help students acquire knowledge about the environment that could be used, rather than facts to be remembered or inert knowledge (Singer et. al., 2000). The instructional framework promoted by LeTUS (Center for learning technologies in urban schools) and UM (University of Michigan) to achieve this goal was based on anchored instruction (Bransford et. al., 1990). Anchored instruction called for creating an authentic task environment where learners could appreciate the utility of the skills and knowledge they were acquiring and furthermore, could recognize the conditions under which these skills were applicable (Bransford et. al., 1990). Teachers guided students with their investigations in this learning environment.

The software. Investigation was scaffolded with the use of computer tools designed to support inquiry. These computer tools included Model-It, e-Chem, and Tool Soup. Model-It provided facilities for creating and testing a qualitative models of cause and effect relations. When using Model-It, learners created objects in the system that they associated variables and defined the relations among the variables to show how the objects effected each other. Immediate effects or effects over time could be modeled. Model-It provided a "Variable Map" for visualizing the model as a whole. After a model was built, students could display the results of the model's behavior in meters and graphs.

The computer tool e-Chem was also used. e-Chem was a visualization tool that allowed students to easily construct and rotate 3-d objects. The screen shot on the next page shows e-Chem molecular visualization software (Wu et. al., 2000).

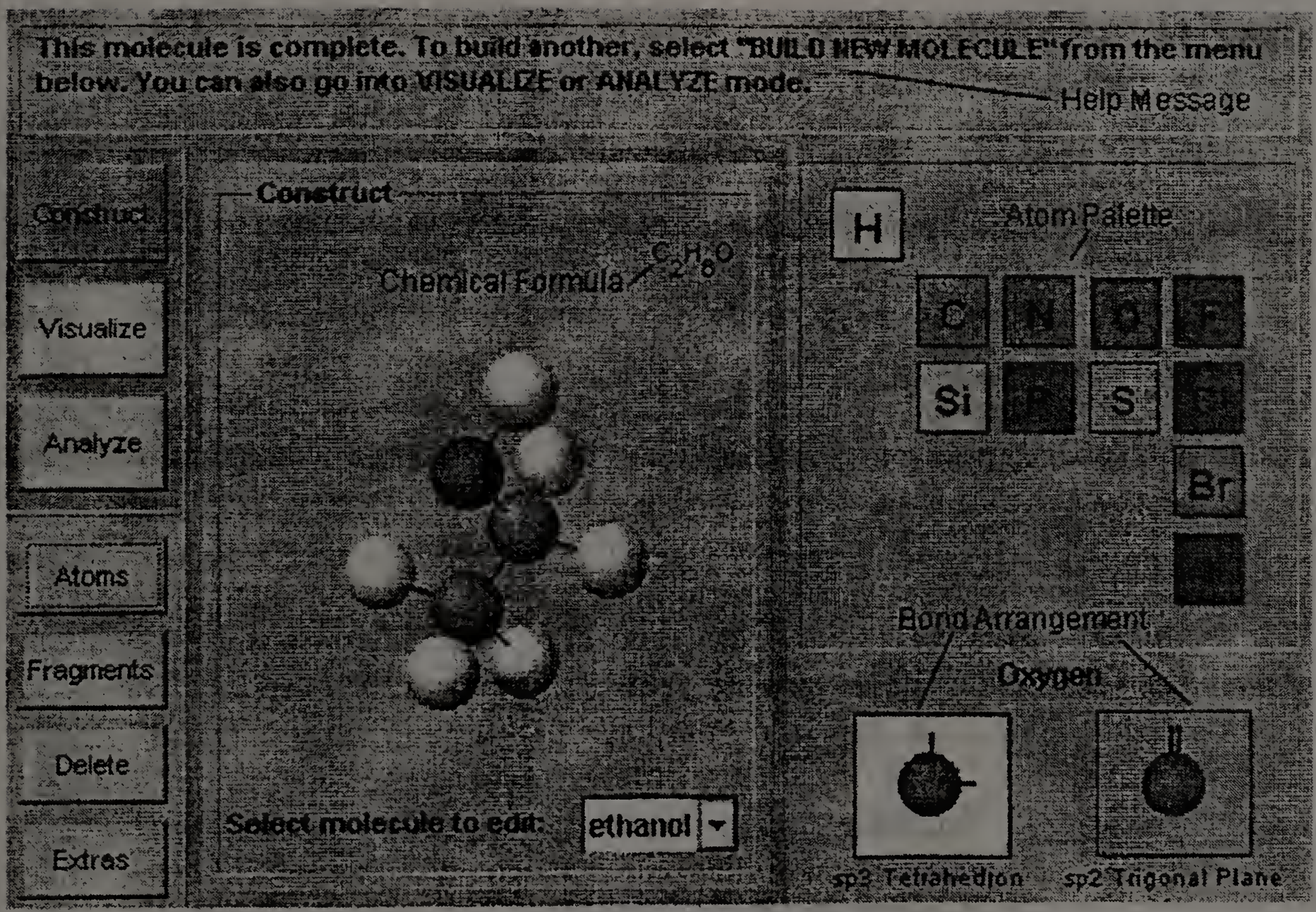


Figure 2. The graphic interface of the *Construct* page.

Tool-soup was also used. Tool-Soup was a large communal database where students could access data from other centers.

<u>Air pollution with Tool-Soup, Model It, and e-Chem.</u> The instruction began with a driving question and an anchoring event. In middle school, students began with a driving question from their real-world experiences. For example, in the environmental studies unit, for the driving question, 'What affects the air quality in my community?', students walked around the school grounds and took pictures of possible sources of pollution as an anchoring event. According to the authors (Singer et. al., 2000), this approach to inquiry using anchoring events allowed students to gain ownership of the driving question.

Model -It was first used by having students go for a walk that focused students on potential sources and effects of air pollution. The teacher then introduced the software. Students drew pictures of 6-8 objects that could effect air pollution using Model-It. The whole class arrived at some consensus on the pictures and objects that should be included in Model-it. The class then constructed a representative class picture using the software.

Benchmark lessons then followed. The lessons focused on content. Students learned about what is air and what they knew and needed to know about air. They then created a picture of air quality and composition that they revisited throughout the unit.

Students modeled air pollutants and compounds from their picture using e-Chem. The computer tool e-Chem was a visualization tool that allowed students to easily construct and rotate 3-d objects. Before using the software, initial models were constructed using gum drops and toothpicks. The gum-drops activity was limited because this activity does not illustrate proper arrangements or multiple bonds. According to the authors, the use of e-Chem helped students create more scientifically acceptable representations of compounds in the air.

Students then read newspaper articles about air quality in their community and acted out a dramatization of air pollution. With scaffolding from the teacher, the class constructed a "know and need-to-know" chart as part of the discussion board. The discussion board allowed the teacher to add more information and explicitly relate concepts back to the driving question.

Students also used Tool Soup. Tool Soup was a database and data visualization tool that contains information about air quality from 10 large urban centers. Tool Soup provided data to students that could help them make comparisons and examine changes in air quality over time. As the curriculum progressed, items on the "know and need-to-know" chart changed.

While the authors conceded that inquiry could be done in classrooms without these learning technologies, they contended that the learning technologies used here such as Model-It, Tool Soup, and e-Chem expanded the range of questions that could be investigated, data that could be collected, isolated, and compared, representations that could be displayed to aid interpretation, and products that could be created to demonstrate understanding (Singer et.al, 2000). The initial designs of this environmental studies unit attempted to engage students in generating questions, making observations, defining variables, modeling relationships, constructing models, comparing data, and verifying the accuracy of the information as several processes associated with an investigative web (Singer et. al, 2000). The design of this learning environment appeared to hold promising strategies for learning (anchoring events, real world investigations, dramatizations, model building, cooperative group work), with the use of interactive computer representations (e-Chem), dynamic modeling tools (Model-It), and communal databases (Tool Soup), but further study is necessary.

2.6.4 Weather with WorldWatcher

Learning Goals. The learning goal in The Create-A-World project was to build an understanding of weather and weather patterns (Edelson, 2001) .

The software. The computer software that was used in The Create-A-World project was called WorldWatcher, a scientific visualization and data analysis program, and the Progress Portfolio, an inquiry support environment where students could record, annotate, create presentations, and organize their projects. WorldWatcher stored and presented information about weather patterns in dynamic and interactive formats. WorldWatcher also contained facilities for students to create novel weather patterns.

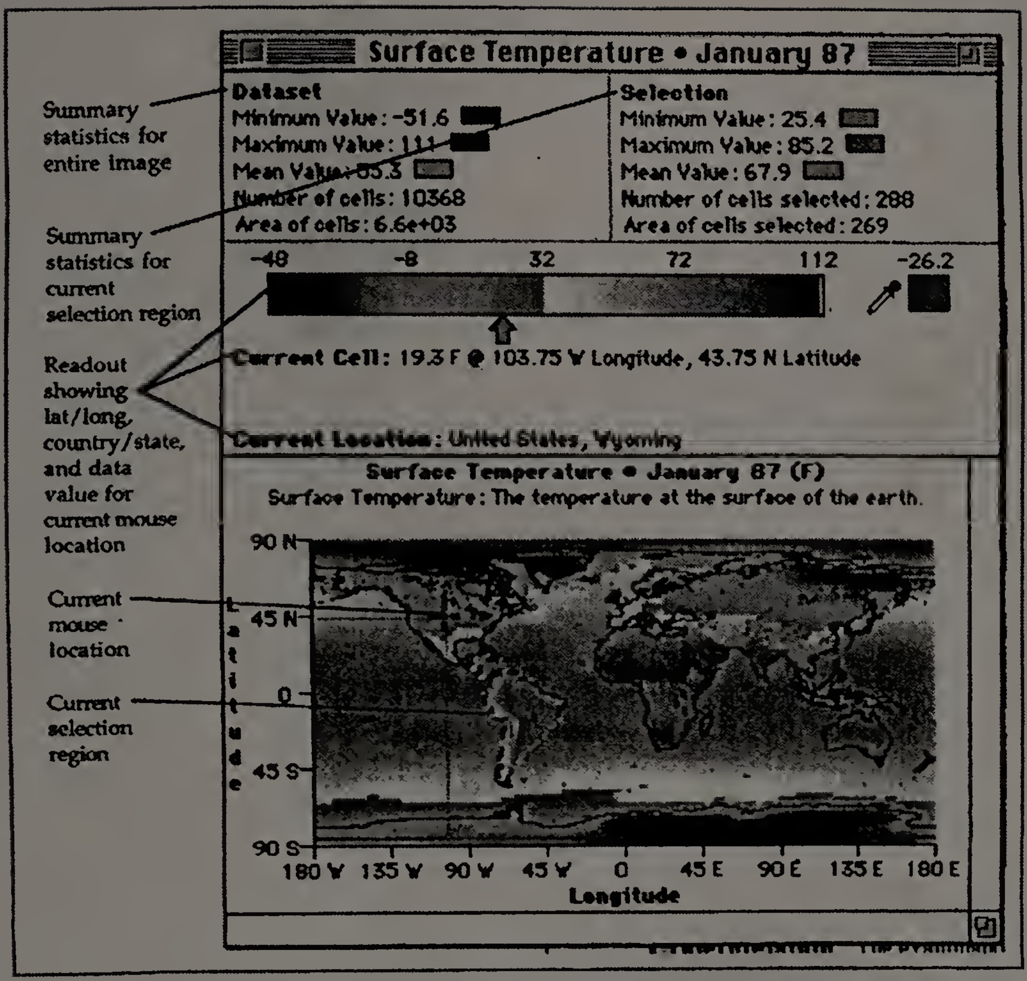


Figure 1. A WorldWatcher visualization window.

__Weather with WorldWatcher.__ Colleagues at the Center for Learning Technologies in Urban Schools created The Learning for Use model (LfU) as an instructional framework for the Create-A-World project (Edelson, 2001). The LfU model of instruction was a three step process consisting of instilling motivation by experiencing the need for new knowledge, constructing knowledge by making links to prior knowledge, and refining that knowledge through application and reflection in order to make the knowledge accessible (Edelson, 2001).

The Create-A-World project was an earth science curriculum for Grade 8 students that focused on the relationship between physical geography and climate. The Create-A-World project involved students doing several activities where they invented data that described a fictitious world's geography and climate and made predictions about the climate there. The first activity asked students to predict temperatures around the world (Earth) in the month of July using blank maps of the world. Students were then taught how to use WorldWatcher to draw data visualizations of their own map.

They compared their WorldWatcher maps with scientific data sets. Students put copies of their maps in the Progress Portfolio and were asked to record the places where their maps came close to the actual temperatures from the scientific data sets and where they were particularly far off.

The students participated in a group discussion about the discrepancies in their maps. According to the author (Edelson, 2001), the goal of this activity was to enable students to begin to observe patterns of temperature variation and to elicit curiosity about their causes. The author believed that students would require the use of their data visualization analysis skills to enable them to compare the patterns in different data sets (Edelson, 2001).

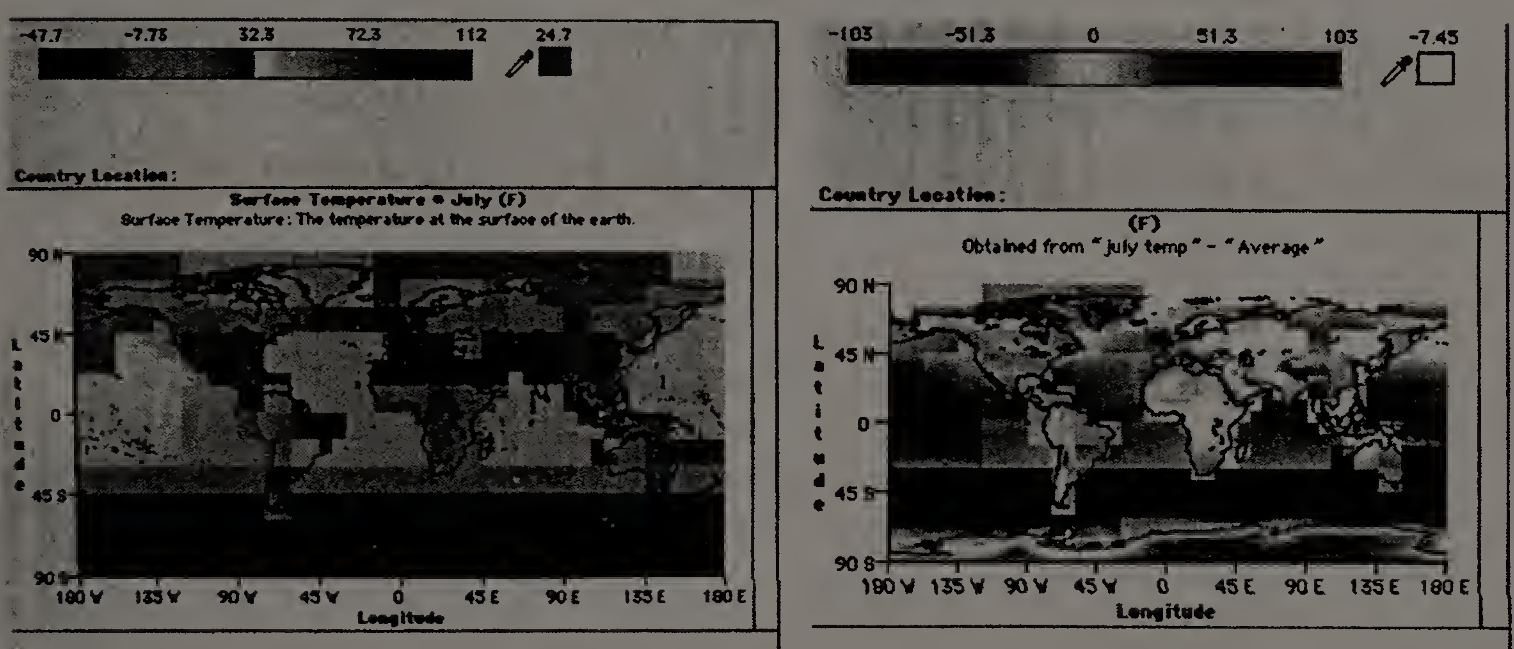


Figure 4. A student-drawn map of July temperature entered into WorldWatcher (left) and a visualization depicting differences between this map and actual Earth surface temperature (right).

In the next activity, students created an alternative topography for a make-believe Earth. Students worked with the tools in WorldWatcher to look for relationships from realistic data sets of different climate regions on Earth. They placed their annotated maps of the Earth world into their Progress Portfolios. Students discussed the relationships as a group and listed their hypotheses of relationships between temperature and physical geography. The teacher asked students to support their hypotheses with information from WorldWatcher. For each relationship, the teacher engaged the students in a discussion of the potential causes of the observed relationships. According to the author (Edelson, 2001), these discussions provided the opportunity for the teacher to offer teacher explanations and address misconceptions. Traditional labs augmented the Create-A-World project by providing an opportunity for students to explore the processes behind the differential heating of a miniature Earth in the lab. Students also measured and did data analysis in the labs. In the final activity, students used the information that they obtained from the labs to adjust their maps in WorldWatcher to account for new information they learned about land-water differences, elevation, and the reflectivity of ground cover from the labs.

The author (Edelson, 2001) concluded by suggesting that there were features in the design of this learning environment that may foster knowledge construction, observation, communication, and reflection with the computer (Edelson, 2001). It also appeared that the design activities with World Watcher may have provided opportunities for students to look for relationships using the surface temperatures map visualization and data set features of WorldWatcher, map predictions using the selection feature in World Watcher, and compare the data sets in order to generate weather patterns. In this way, students may have been engaged with several of the processes associated with scientific inquiry in the Create-A-World project, but more work is necessary.

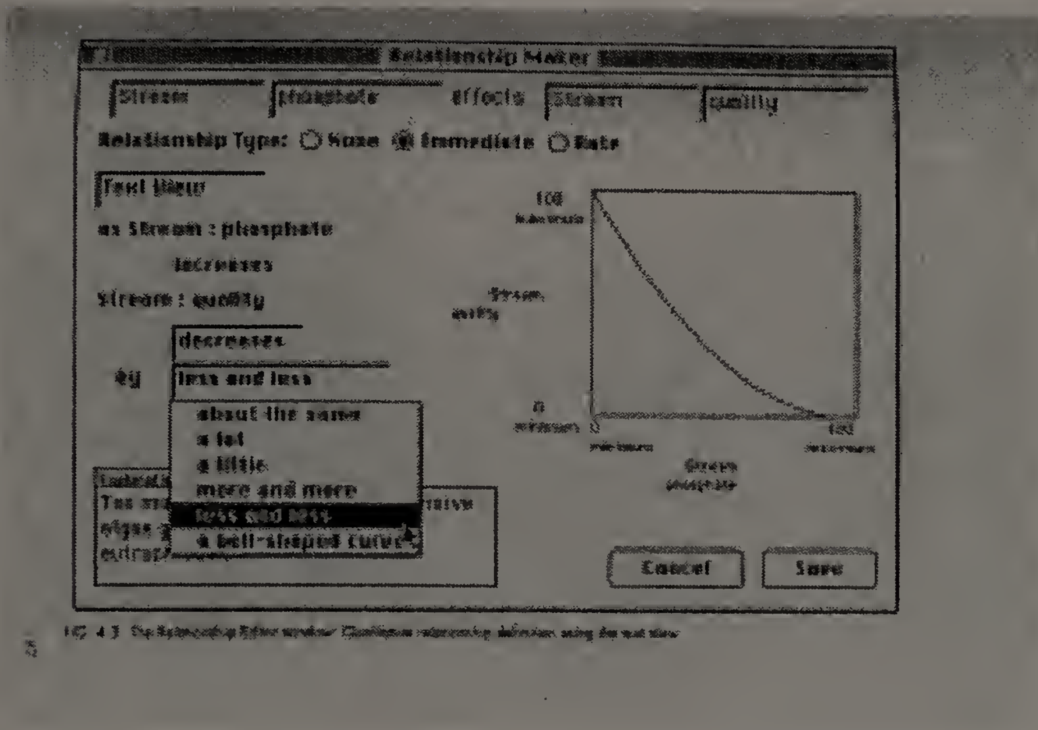
2.6.5 Stream ecosystems with Model-It

Learning Goals. One of the learning goals of a unit on ecosystems was to create a model of a stream ecosystem (Stratford, et. al., 1998).

The Software. In this study, 16 9th grade science students worked with Model-It to make original models of 5 different stream ecosystem scenarios. The Model-It software had an object feature, a factor feature, relationship feature, and a Factor Map. The student created objects in the Object Factory using available icons (i.e. the object is an environment, individual, or population). The student created a name and identified the object "type" that would have effects on its behavior and relationships.

Students selected factors. Factors could include the temperature of the stream, the speed of the wind, the number of people, or the size of the golf course. Factors could also be mathematical constructs such as the rate of growth of a population, count individuals in the population, or the rate of decay. In the Factor Factory for the ecosystems model, for example, the factor pond depth was selected and assigned an initial value.

Model-It did not require the user to make the difference between causal and correlational relationships explicit; however, there was a relationship maker feature also that asked students to select a general type of relationship (i.e. none, immediate, or rate) between factors. Relationships could also include "increases or decreases a little" or "a lot" as listed in the pull-down menu (by default, Model-It created all immediate factors as "increases about the same"). A text view, for example, stated for the pond: suspended solids increases, pond: depth decreases by about the same. A table view, however, required that students input values, and a rate view would have 'add water runoff: average rate to pond: suspended solids'. A graphical representation of the relationship was produced and an accompanying window where students could input an explanation for this relationship was available. Relationships could be modeled immediately or for effects over time. The screen shots on the next page (found in Jacobsen & Kozma, 2000) shows Model-It modeling software (Stratford, et.al., 1998).



Running the model displayed a Factor Map where the name and an icon of the object was associated with arrows to other objects in the map or "web". The color of the arrow represented relationships (a black arrow was an immediate relationship; a gray arrow was a rate relationship) between the two objects.

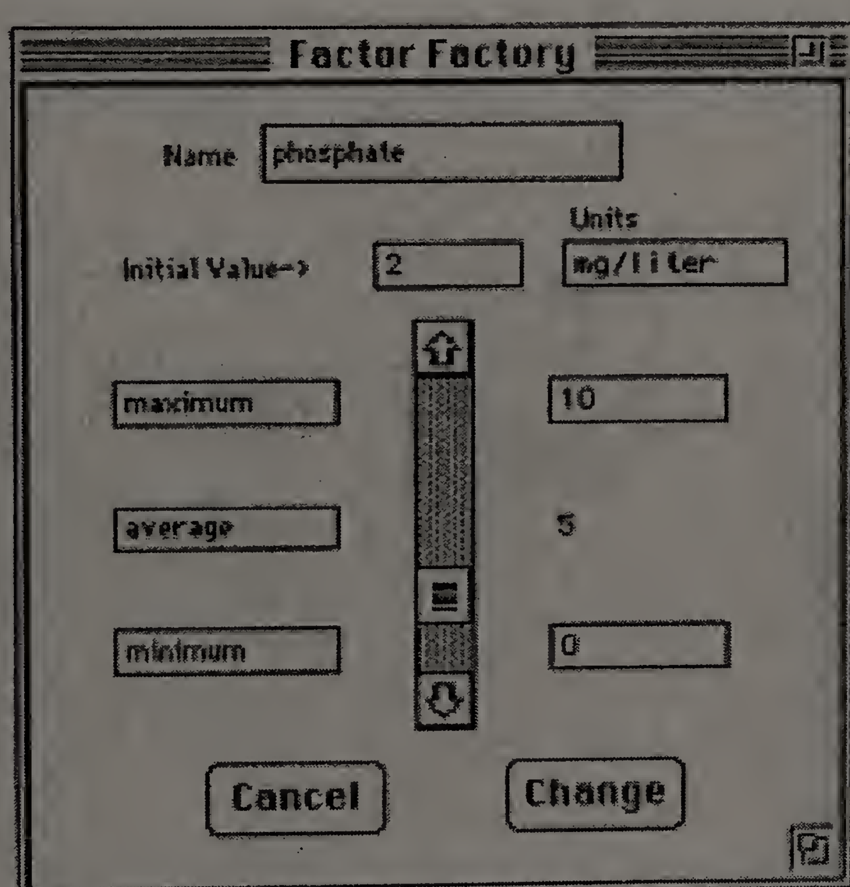


FIG. 4.2b The Factor Editor window, editing the phosphate factor.

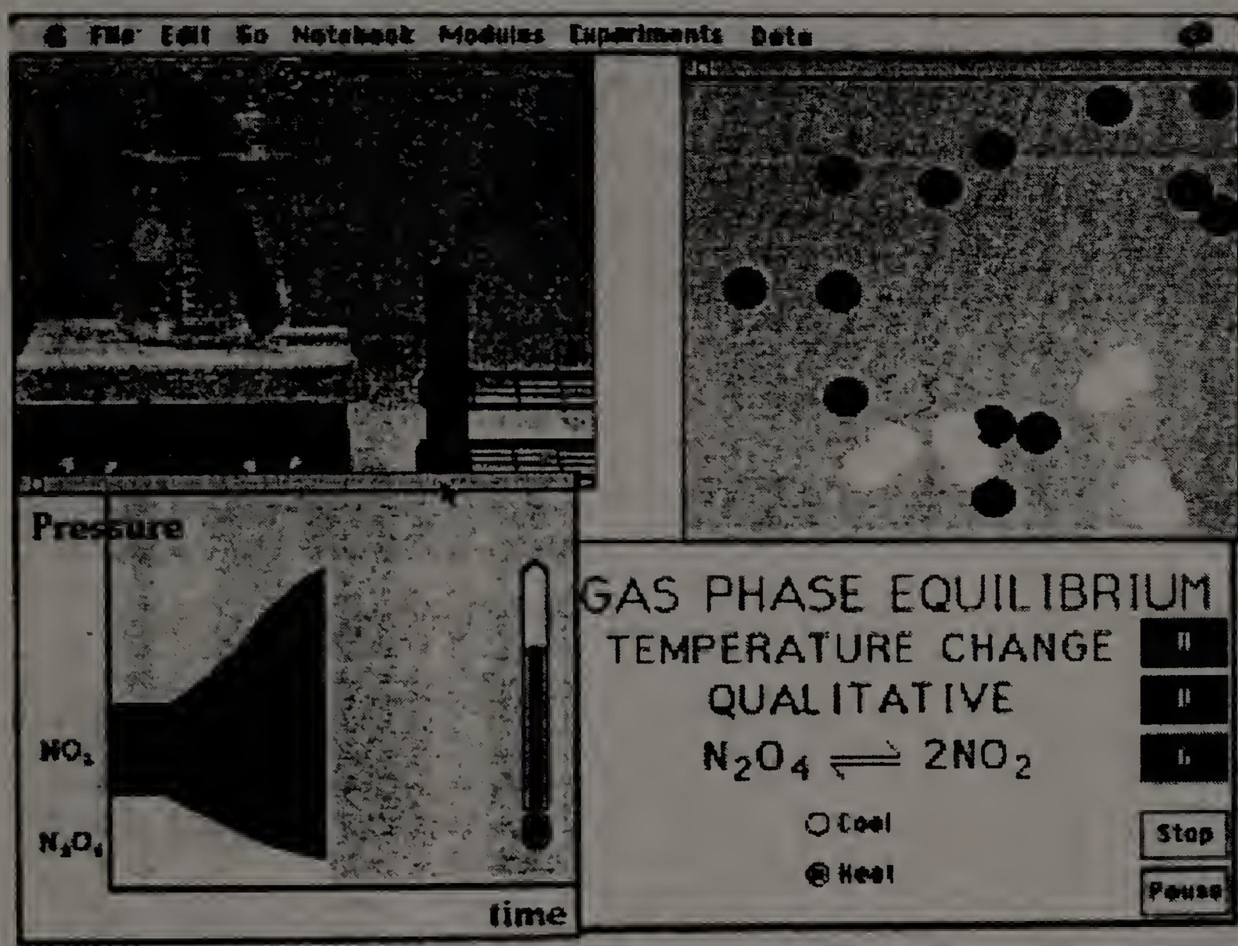
In addition, meters and graphs dynamically changed to show the changes in the system. Model –It provided facilities for testing a model and a "Factor Map" for visualizing it as a whole. The teachers expected the students to enter explanations and descriptions for all of the objects, factors, and relationships they included in their model.

Stream ecosystems with Model-It. For 6 one hour periods, students worked with a written guide to prepare them for creating the models using Model-It. The researchers (Stratford, et. al., 1998) reported evidence of analyzing, relational reasoning, synthesizing, testing/debugging, and explaining from videotapes of students who produced low, moderate, and high quality models as students worked with Model-It to produce models of stream ecosystems. Although there was evidence of these student behaviors (Stratford, et. al., 1998), the authors stated that for all students to progress beyond making somewhat superficial relationship connections, additional guidance was necessary. There were, however, several preliminary aspects of this learning environment that appear to have demonstrated some early success; that is, students appear to have been engaged in analyzing information and generating and testing relationships in this learning environment; however, more information is needed to verify this early finding.

2.6.6 Chemistry with 4M: Chem

Learning Goals. This chemistry learning environment encouraged students to increase their understanding of chemical equilibrium (Kozma, 2000).

The Software. The software used in this learning environment was entitled MultiMedia and Mental Models in Chemistry or 4M: Chem (Kozma, 2000). 4M:Chem consisted of multiple, linked representations of chemicals and chemical equations. Students could manipulate parameters such as temperature or pressure using 4M:Chem. Students could also view the effects of their actions as they propagated through simultaneously displayed multiple dynamic representations. These representations included a video for the chemical reaction and molecular level animations. The screen shot below (found in Jacobsen & Kozma, 2000) shows 4M:Chem chemistry software.



2 Sample screen from 4M:CHEM showing video, animation, graph, and control windows open. Original in color.

<u>Chemistry with 4M: Chem.</u> The instructional framework for the chemistry learning environment followed a Predict-Observe-Explain (POE) and conclude cycle of instruction. Students received a manual that directed them through a series of experiments related to the chemistry concept of equilibrium following the predict-observe-explain and conclude cycle. For example, students were asked to predict the results of an increase in pressure on the system, make observations of the results of the video experiment and explain and draw conclusions about the nature of chemical equilibrium. Following the video of the reaction and dynamic displays, graphs, and animations, a voice narration identified the linkages across all of the different representations. The voice narration directed students' attention to key features in each representation and described what was occurring. For example, after the animation was played, a narration said, "As time passes, notice that the average speed of the red and white molecules increases" (Kozma, 2000).

Two studies were conducted with POE and 4M:Chem (Kozma, 2000). The first study separated the video, graph, and animations in an experiment and compared these three groups with a fourth group of students that worked with all three representations (the VGA group: video, graph, animations and audio narration) in 4M:Chem (16 students in total). The students worked individually with the software and a manual. A pre and post test was administered measuring students' understanding of equilibrium. As a whole, all of the groups improved their understanding as measured by the pre and post tests, but there were no significant differences between groups in general on the overall score. The animation group, however, did significantly better on items dealing with the dynamic nature of equilibrium, and students in the graph group did significantly better on questions dealing with relative proportions and concentrations of reagents. However, students in the VGA group (the group with all the representations: video, graphs, and animations) did no better than the students in the other groups.

In the second study, Kozma (2000) wanted to encourage argumentation and explanation so they removed the audio narration in the software and added questions to the student manual that asked students to explicitly identify the function of certain surface features of each of the representations using all 3 representations. The predict-observe-explain format was maintained. Kozma (2000) examined the types of discourse moves and found students encountering dissonance, making meaning, and confirming when they had to explicitly identify the function of certain surface features of each of the representations using all 3 representations. Kozma (2000) concluded that using 4M: Chem in this context may have resulted in sustained inquiry and an extended consideration of the representations in chemistry compared to the first study. Kozma

(2000) contended that students in the second study with 4M:Chem replicated the discourse practices observed in studies of scientists interpreting the meaning of representations in their laboratories.

2.6.7 Chemistry with e-Chem

Learning Goals. In this learning environment, students were encouraged to learn chemistry with multiple computer representations and externalize their understanding of environmental toxins (Wu, et. al, 2001).

The Software. The software used in this learning environment was e-Chem. e-Chem was a chemistry visualizing tool that contained tools to build molecular models and simultaneous views of multiple representations. Unlike 4M:Chem, e-Chem provided students with the opportunity to create artifacts and externalize their understanding, according to the authors (Wu, et. al, 2001). Students could not change or create any representations in 4M:Chem; whereas in e-Chem, students were able to construct representations. With e-Chem, students could build molecular models, visualize multiple 3-D models, and compare micro and macroscopic representations for analysis (Wu, et. al, 2001).

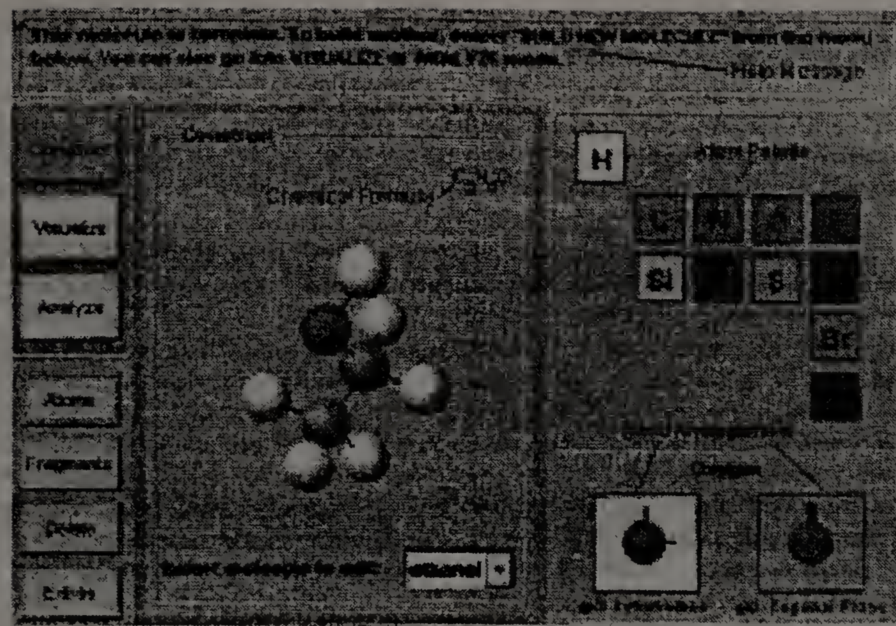


Figure 2. The graphic interface of the Construct page.

<u>Chemistry with e-Chem.</u> The instructional framework for a unit on environmental toxins followed the anchored instruction (Bransford et. al., 1990) model and began with a driving question, an anchoring event, and followed with benchmark lessons. The computer tool e-Chem (Wu, et. al, 2001) was integrated into a 6 week curriculum project called the Toxin Project. The Toxin Project began with 3 high school teachers providing a list of known toxins to their high school chemistry class. Students (n=71) worked in pairs and selected a known toxin to investigate. The driving question was: is my drinking water safe? Students listened to lectures on concepts in chemistry, searched for information from the Web, carried out lab activities on solubility and water purification, built physical and e-Chem models and designed Web pages for their final projects.

The first activity with e-Chem was where students constructed models of alkanes and viewed multiple representations of the alkanes. The purpose of the activity was to develop an understanding of the relationship between boiling points of alkanes and the number of carbon atoms.

In the second activity, students created models on e-Chem and followed naming conventions to name their models. Students visualized 2-D and 3-D chemical representations with e-Chem and compared differences between these types of models.

Wu, et. al, (2001) claimed e-Chem was used throughout the entire unit with the teacher making reference to e-Chem when they introduced the concepts of molecules, to covalent bonds, and to molecular structures. Pre and post tests were administered to students to test their understanding of macro and microscopic levels of chemical representations. Wu, et. al (2001) found that there was a significant improvement. According to the authors, interview data suggested that the action of selecting bond arrangements appeared to strengthen and build students' conceptual linkages among bonding, structures, and molecules. Second, according to the authors, the model rotation feature provided by e-Chem appeared to assist students in making visual connections between 2-D and 3-D models (Wu, et. al, 2001). This learning environment may have fostered students engagement with lab activities, model construction and making comparisons in chemistry with e-Chem.

2.6.8 Discussion of computer-enhanced learning environments

Designs of learning environments. Although there were many different learning goals and content areas that were surveyed, the design of these learning environments shared two major characteristics in common: they were designed to sustain a process at some level. The process was supported or enhanced with the integration of computer tools. Secondly, a general instructional approach was apparent in the lessons. This instructional framework was driven by theories on how people learn science and goals for learning. The instructional framework embedded structured activities for students and groups of students, and students were not left in any case just to "explore." The three tables below summarize the major concept and main teaching methods within computer affordances for instruction, and the role of the teacher as described by the study.

Table 2. Survey of concepts and teaching methods.

Design of Learning Environment with software	Concepts	Methods
White and Frederiksen (2000)	Force and motion	Inquiry cycle Simulated and real world physics experiments Reflection and assessment
Hafner & Stewart (1995)	Mendelian genetics	MRSPG-Model revising problem solving in genetics Actor explains simple dominance model Simulated genetics experiments Practice simple and codominance problems
(Singer et. al, 2000)	Air pollution	Investigative Web Anchored instruction with driving question, anchoring event, then benchmark lessons that included outdoor labs, classroom discussions, performance, and modeling activities
(Edelson, 2001)	Weather	Learning for use model (LfU) Create a world and compare weather patterns in their fictitious world with actual scientific data sets Do labs with a mini-Earth model to learn about land water differences, elevation, and reflective ground cover Whole class discussions of causes of weather patterns
(Kozma, 2000)	Chemical equilibrium	Predict-Observe-Explain and draw conclusions Small groups Manual with software that asks students to make predictions, explicitly identify the function of certain surface features of each of the representations

Design of Learning Environment with software	Concepts	Instructional Methods
		and construct explanations
(Wu, et. al, 2001)	Chemical pollution	Anchored instruction

Table 3. Survey of computer affordances.

Design of Learning Environment with software	Software Features	Computer Affordances
Thinkertools White and Frederiksen (2000)	Models of force and motion Students can change properties of objects, turn friction and gravity on or off, place barriers on the screen, select different friction laws, show velocity, pause simulation	Test ideas about force and motion in frictionless environment Proceed step by step in the simulation, pause, and discuss Select variables, measure changes quickly
Genetics Construction Kit Hafner & Stewart (1995)	Simulated Genetics lab Select fruit flies and cross them Traits and variations of offspring are displayed	Quickly do a large number of fruit fly crosses (more efficient than a lab) View results of a large number of fruit fly crosses quickly
Model-It, e-Chem, Tool-Soup (Singer et. al, 2000) (Wu, et. al, 2001)	Model sources and effects of air pollution (Model-It) Construct molecular models of compounds in air (e-Chem) Scientific database of air quality from 10 cities (Tool Soup)	Model systemic effects of multiple sources of pollution simultaneously Select objects, relationships, and measure changes quickly Construct, change, and easily rotate 3-D objects that have proper arrangements and multiple bonds. Micro and macroscopic views of 3-D models Access large amounts of data on air quality from urban centers, past and present

Design of Learning Environment with software	**Software Features**	**Computer Affordances**
WorldWatcher (Edelson, 2001)	Create and visualize fictitious worlds with different temperature variations, alternative physical topographies Access scientific data sets from different climate regions Progress Portfolio to collect surface temperatures maps	Invent data and visualize the weather View differences in topographies and surface temperatures quickly and look for relationships using color coded surface temperatures maps Predict climates with blank maps, select variables, and create a world with new weather patterns generated quickly Compare large data sets in order to generate weather patterns
4M:Chem (Kozma, 2000)	Multiple linked representations including video of the chemical reaction, graphs, molecular level animations, and narration of chemical equations Change temperature and pressure parameters in simulations Video of chemistry experiments Graphical output	View animations of unobservable processes Change variables to extremes View dangerous chemical reactions on video Voice narration directs student to key features in the representation. Representations color coded. Dynamically generate graphical output quickly Cannot change or create representations

Table 4. Survey of teachers' roles.

Design of Learning Environment with software	Role of the teacher described	Descriptions of Teaching strategies
White and Frederiksen (2000)	Guide Provider Assessor	Suggesting the need to simplify the research question, giving experiments, picking assessment criteria and asking students to rate the presentations
Hafner & Stewart (1995)	Actor Lecturer	Actor portraying "Gregor Mendel" describes the problem he was dealing with as well as his explanatory model Teacher develops a model of the process of meiosis
(Singer et. al, 2000)	Helper Introduce software Scaffolds Relates concepts back to driving question	Teacher helps students create sub questions to from driving question. The teacher introduces the software. With scaffolding from the teacher, the class constructs a "know and need-to-know" chart and teacher relates back concepts to the driving question.
(Edelson, 2001)	Question	Teacher asks students to support their rules with observations from WorldWatcher. For each relationship, the teacher asks students to discuss the potential causes of the observed relationships.
(Kozma, 2000)	Manual	There was a manual with questions
(Wu, et. al, 2001)	Reference Lecturer	Provides lists, makes references to software

From Table 2., it appears that all of the designs of the learning environments had an instructional framework that ranged from an inquiry cycle, the MRSPG model, the Investigative Web, the LfU model, to POE. The instructional framework contained several structured activities that were described more fully in each of the respective studies, such as real-world labs, small groups arriving at consensus, or problem solving activities. These activities appeared to address multiple processes associated with inquiry such as testing ideas, making comparisons, and collecting data to name a few. The computer was fully integrated into instruction, and with the computer, students tested ideas, made comparisons with large scientific data sets, modeled systemic effects or modeled 3-D molecular structures, dynamically generated graphs, collected information, or viewed multiple representations, as listed in Table 3. The scarcity of detailed information about the teacher's role, however, was notable in Table 4. There were limited descriptions and prescriptive measures of how teachers could implement the instructional frameworks and guide students through the structured activities with the computer to accomplish learning goals.

Limited descriptions of teachers' roles in the designs of learning environments. A survey of the designs of learning environments that were examined above revealed a relative scarcity of information on teaching methods in these environments, compared with the more explicit discussion of the general instructional framework and the software features. For example, the role of the teacher was described as: suggesting the need to simplify the research question, giving experiments, picking assessment criteria and asking students to rate the presentations in the Thinkertools curriculum (White & Frederiksen, 2000).

In the genetics learning environment with GCK (Hafner & Stewart, 1995), the study described a "modeling" and a "black box" activity where students made inferences about the causal mechanisms of an unknown "system" hidden inside the box. Students read portions of a translation of Mendel's work and received a visit from an actor portraying "Gregor Mendel" who described the problem he was dealing with as well as his explanatory model. It was possible that the modeling activity was led by the teacher and that the teacher was acting as Gregor Mendel in this moment. The study also suggested that the teacher developed a model of the process of meiosis, but there were no suggestions on how this was accomplished.

In the air pollution study (Singer et. al, 2000), the teacher was described as helping students create sub questions to ensure students understand the scope and breadth of the relationships that come to bear. An anchoring event then attempted to anchor the sub question in a real world context. The teacher then introduced the software. It was suggested that students learn about what is air, and identify what do they know and need to know about air, but there were no descriptions on how this was done. The study stated that with scaffolding from the teacher, the class constructed a "know and need-to-know" chart as part of the discussion board and suggested that a discussion board allowed the teacher to add more information and explicitly relate back concepts to the driving question.

In the WorldWatcher learning environment (Edelson, 2001), the role of the teacher was described as asking students to support their rules with observations from WorldWatcher that led them to propose the rule and their initial explanations for those observations. For each relationship, the teacher then engaged the students in a discussion of the potential causes of the observed relationships.

The teacher's role in Model-It learning environment was described as expecting the students to enter explanations and descriptions for all of the objects, factors, and relationships they included in their model. The teacher's role in the 4M:Chem learning environment was not mentioned in the study, although a manual did exist for the students (Kozma, 2000), and in e-Chem, it was stated that the teacher made references to e-Chem when they introduced the concepts of molecules, covalent bonds, and structures (Wu, et. al, 2001).

While there may have been more prescriptive measures that were described elsewhere for these learning environments, in the studies that were reviewed here, the teacher's role was not elaborated further than these statements. The strategies for teaching within these learning environments ranged from statements such as, 'give experiments, to develop a model, scaffolding and explicitly relate concepts to questions'. While many expert teachers may understand how to "scaffold" and "explicitly relate concepts to questions", these descriptions may not be sufficient prescriptive measures for novice teachers who wish to adapt this learning environment to their classroom. The teacher's role was important since it was clear that the computers were not teaching the concepts, directing the investigations, or guiding inquiry in these cases. The scarcity of prescriptive measures for teachers within these learning environments represents a gap in the current research that could prove problematic for teachers who are interested in adapting these methods to their science classrooms.

2.7 Chemistry with Chemland

2.7.1 Brief introduction to the case study

Briefly, this case study investigated the design of a learning environment in an introductory chemistry class, its instructional framework, and the use of interactive computer tools. The learning environment was an introductory chemistry class. The learning goals included the major concepts in chemistry of a standard introductory chemistry curriculum at the college level. Chemland software was fully integrated into the class. Chemland software presented large amounts of information to the students in multiple ways. The software did not teach students' concepts or how to use the information.

2.7.2 Goal of the case study

One goal of this case study was an elaboration on teaching methods, activity structures, and specific teacher guidance strategies that were designed by the teacher to trigger and facilitate inquiry in this introductory chemistry class. Recent literature suggests that teachers who are consulting national standards needed more rich descriptions of what these learning environments look like in the classroom and rich descriptions of what the teachers role is in these learning environments (Keys & Bryan, 2001). Indeed, there appears to be a scarcity of literature on the area, especially in computer-enhanced learning environments (Hafner & Stewart, 1995; Singer et. al, 2000) in chemistry (Kozma, 2000, Wu, et. al, 2001). Keys and Bryan (2001) reiterated that more research is needed that develops rich descriptions of teaching strategies. While adaptation into the classroom clearly requires more than best practices, an explicit description of the teaching methods designed by the teacher may provide the kind of detailed, prescriptive teaching strategies that other science teachers are requesting in order to attempt inquiry in their classrooms. A goal of this case study, therefore, is to provide explicit descriptions of teaching strategies in this computer enhanced learning environment for inquiry.

Thus, the sub questions of this case study are:

1. What were the instructional strategies and interactions in this class?
    a. What was the instructional approach using computer tools in this class?
    b. What were the activity structures and specific guidance strategies?
    c. What were the teacher, student, computer interactions in this class?
2. What were the major learning processes that are triggered during instruction?
3. How did the teacher's behavior support learning?
    a. What activities and guidance strategies triggered learning?
    b. What did this learning look like and how could it have possibly improved students' inquiry skills?

2.7.3 Scope and delimitations of the case study

Despite the promising designs of learning environments that have recently emerged, there were few that operated within a chemistry classroom (Kozma, 2000; Wu, 2001), and few that were investigated and reported evidence on the design of a learning environment beyond a domain-specific topic or lesson (Model-It). Also, compared with physics and biology where there is much more research, we are still searching to develop promising models of learning environments in chemistry that report evidence for sustained student engagement with concepts and processes throughout a course curriculum. Thus, the scope of the study is on a single introductory chemistry class plus 2 additional introductory chemistry classes at the same institution. Furthermore, the examination of these classes will span the entire curriculum and the entire semester in this study.

The case study reported here of the design of a learning environment in Chemistry with Chemland software addressed several of the processes currently associated with inquiry and incorporated the use of relatively modest computer tools designed for concept learning. Thus, the study was limited to an examination of several processes currently associated with inquiry and not all of the dimensions of scientific inquiry. Furthermore, the study may have been limited by the selection of particular technologies (Chemland software) that were generally limited to simulations of lab results in this classroom compared with the more powerful technologies (WorldWatcher, Model-It and Tool-Soup) that consisted of computer tools for searching databases, collecting information, modeling, annotating and communicating.

CHAPTER 3

RESEARCH DESIGN & METHODS

3.1 The case study approach

Model based learning theory with a case study method. Model based learning theory with a case study method is a framework that allows one to trace the effect of innovative teaching strategies on classroom student processes and post course outcomes (Clement, 2002). The overall approach to the research design followed the case study tradition of qualitative research methods. A single case study is an empirical inquiry that investigates a contemporary phenomenon within its real-life context, especially when the boundaries between phenomenon and context are not clearly evident (Yin, 1994). A case study approach was selected instead of an ethnographic or phenomenological approach because the study focused on an instructional strategy in a classroom rather than a cultural phenomenon or an in-depth analysis of any particular individual.

The case study approach appeared appropriate for this analysis because it allowed the flexibility to explore the classroom context as a whole while simultaneously focusing on the individual learner as well. The case study produced a detailed description of the major teaching strategies and learning processes that occurred in an introductory chemistry classroom that integrated interactive computer tools. This classroom is referred to as the primary case.

A "method of contrasting cases" was also employed in this study where the primary case was compared with two other introductory chemistry classrooms (lecture 1 and lecture 2) in the same chemistry department. Although lecture 1 and lecture 2 covered the same syllabus and were offered at the same institution as the primary case, they were different in many other aspects—including approaches to instruction. The inclusion of lecture 1 and lecture 2 in the study was, therefore, not intended to serve as a controlled comparison to the primary case that isolated the variable of teaching approach to look for effects of that variable alone. However, in a method of comparative case studies, one can still ask the question, what is the most viable hypothesis for why the primary case was the only group to show a significant gain in process skills? Thus, the purpose appropriate to a case study is to generate the most viable hypothesis rather than to test a particular hypothesis. A purpose of including descriptions of lecture 1 and lecture 2's approaches to instruction was as an attempt to acquire initial data on the question of whether the primary case teacher's methods departed in a significant way from the normal teaching methods used in the chemistry department.

The contrasting case methods provided initial contrasts that could be used to stimulate the design of later studies with larger samples. The introductory chemistry class that integrated interactive computer tools is referred to as the "primary case" and the two contrasting cases are referred to as "lecture 1 and lecture 2" for the remainder of the case study.

Furthermore, qualitative case studies of instructional interactions to identify key issues, concepts and variables were therefore an important and appropriate foundation for the project. But the study also included quantitative measures, as key variables were identified and coding or issue based surveys became possible and appropriate (Clement, 2000). Thus the study used a mix of qualitative and quantitative methods.

To ensure trustworthiness of the findings and generalizations, specific checks were built into the study. They included checks to ensure that the data had been gathered accurately, analyzed critically, and interpreted in context. These checks are described throughout the data collection methods and the data analysis sections.

3.2 Units of analyses

The primary unit of analysis was an introductory chemistry class that integrated computer technologies into the classroom (Vining, 2000). Two additional introductory chemistry classes at the same institution were also observed. Thus, there were three introductory chemistry classes that were examined; however, the focus of the case study was on the primary case.

This section briefly describes the three introductory chemistry classes in the table below--the primary case, lecture 1 and lecture 2. More detailed descriptions of the classrooms are included in the results section of the study.

Table 5. Three introductory chemistry classrooms.

Intro chem	The Primary case	Lecture 1 class	Lecture 2 class
Students	Honors + non-honors science, engineering, and chem majors	Non-honors science majors, non-science majors, honors science and non-science majors	Non-honors science majors + non-science majors, honors science and non-science majors
Class content	Department-wide introductory chemistry syllabus	Department-wide introductory chemistry syllabus	Department-wide introductory chemistry syllabus
Class size	Small	Large	Large
Teacher's goals	Content and process goals	Content and process goals	Content and process goals
Teaching strategy	Guided discovery approach	Traditional lecture approach	Modified guided discovery approach for large lecture

3.3 Sources of data

The sources of data were both qualitative and quantitative in nature. The qualitative data included classroom observation notes and a new approach to the taped think-aloud interviews called the in-depth pair session (Hogan, 1999; Khan, 2001). The quantitative data included classroom observation rubrics, CAT surveys, and a test for conceptual understanding given to a subset of the students enrolled in the primary case. The instruments are described more fully in the next section.

Table 6. Data sources and timeline.

<table>
<tr><th>Case</th><th colspan="5">Data Sources</th></tr>
<tr><td>Chemistry Lecture 1</td><td>Pre-CAT Survey</td><td colspan="3">Classroom observations</td><td>Post-CAT Survey</td></tr>
<tr><td>Chemistry Lecture 2</td><td>Pre-CAT Survey</td><td colspan="3">Classroom observations</td><td>Post-CAT Survey</td></tr>
<tr><td rowspan="2">Chemistry Primary case</td><td rowspan="2">Pre-CAT Survey</td><td colspan="3">Classroom observations</td><td rowspan="2">Post-CAT Survey</td></tr>
<tr><td>Pre- Concept Test</td><td>In-depth pair session</td><td>Post-Concept Test</td></tr>
<tr><td>Time</td><td>Early</td><td colspan="3">Middle</td><td>End</td></tr>
</table>

One to three observers visited the classrooms and recorded all classroom events using notes. Classroom observations were written in the detached open ended narrative form, and memos (Straus, 1987) were written after each observation as personal notes and reflections to the observer. The following observation protocol was followed.

Observation Protocol

1. Observers gathered to review purposes of collecting observation data in biology, chemistry, and natural science classrooms. Observers determined that one of our goals was to be able to characterize the classroom, characterize the instructor's teaching style, describe the interaction between students, and cite evidence of critical thinking skills. Observers developed a series of open ended observation questions to guide us.

2. Observers attended the class. Observers were free to visit the classes without notice on any day it was meeting during the semester. Students were introduced to the data collectors and the purposes of the classroom observations. During this introduction,

they were asked to sign a volunteer consent form to permit observations of their classroom interactions.

3. During each classroom visit in introductory chemistry (primary case, lecture 1, lecture 2), all classroom interactions were fully recorded in the form of observation notes. Observation notes were written in a detached open ended narrative format (Straus, 1987) by the principal observer, S. Khan[5], who recorded as much of the classroom interaction between student groups and the students and the teacher in the classroom as possible using pen and paper. Co-observers, if present, recorded their observations of classroom interactions.

4. Documents from the class were obtained including syllabi, worksheets and any schedules.

5. After recording classroom dialogue as detached open ended narratives in chemistry, a reflective memo (Straus, 1987) highlighting key interactions was written after the lesson was observed.

6. The kinds of interaction between students and the instructor were then coded in the classroom observation rubric[6]. If a co-observer was present, a debriefing meeting took place where the coded classroom observation rubrics were compared for reliability.

7. The REAL[7] group met to share their classroom observations and rubrics (see next section for rubric) for critical discussion several times throughout the year.

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5 The principal observer, S. Khan, had taken several graduate courses in qualitative methods in educational research. In addition, Khan had previous experience with writing case studies of innovations in college science. A large portion of these case study rested on critical observation. Khan was familiar with the observation setting and the instructors, having observed their classrooms in years previous to this study. Co-observers were advanced doctoral students in education and psychology.

6 Refer to Table 7.

7 The REAL group is the center for Research in Education and Learning in the School of Cognitive Sciences at Hampshire College, US

Thus, the data gathered from the classroom observations were: observation notes and classroom documents, memos, and observation rubrics and co-observation rubrics.

3.3.1 Classroom observation instrument

Two years prior to the study, a classroom observation rubric was designed to record frequencies of classroom activities according to categories of activities associated with scientific inquiry. The activities were coded by method of instruction, time segments, and whether they originated from the instructor (I) or the student (S). There were 9 categories of methods of instruction and 6 major categories of classroom activities.

<u>Methods of Instruction.</u>

<u>Whole class/teacher interaction</u>: 1. Prepared lecture 2. Lecture/discussion
3. Discussion 4. Hands on activity
<u>Small Group activity</u>: 5. Discussion 6. Hands on
<u>Student presentation</u>: 7. One or more
<u>Individual activity</u>: 8. Hands on 9. Thinking/writing/reflecting

<u>Classroom activities.</u> There were 6 major categories of classroom activities: generating ideas, gathering information, critiquing results or conclusions, primary literature skills, verbal skills, quantitative skills, and content. Each category contained codes and the criteria for those codes. For example, generating ideas contained the codes: questions, predictions & rules, experimental designs or tests, and explanations or conceptual models, and the criteria for those codes.

The coding process consisted of examining the class observation notes and recording the time and the method of instruction throughout each class. The time segment changed when the method of instruction changed. The observer then applied the categories and codes to the classroom events within the time segment. That is, the observer recorded whether the event was an instructor action to promote or model (I) or student evidence (S) of the activity. The observer recorded the frequency of that activity in that time segment using ranges, where 0 meant the skill was not observed within that designated portion of the classroom period; 1 meant the skill was observed 1-2x in that designated portion of the classroom period, 2 meant the skill was observed 3-5x in that designated portion of the classroom period, and 3 meant that the skill was observed greater than 5x in that designated portion of the classroom period.

Classroom Observation Rubric

Methods of Instruction.

Whole class/teacher interaction: 1. Prepared lecture 2. Lecture/discussion

3. Discussion 4. Hands on activity

Small Group activity: 5. Discussion 6. Hands on

Student presentation: 7. One or more

Individual activity: 8. Hands on 9. Thinking/writing/reflecting

Table 7. Classroom observation rubric.

Instructor actions to promote or model = I Student evidence = S		Time: Method: I	S
Generating Ideas	Questions for or as a result of inquiry		
	Predictions (simple hypotheses) or rules concerning simple relationships between variables		
	Experimental Designs or Tests		
	Explanations or Conceptual Models (causal or mechanistic explanations – why or because. Could be done before or after testing, reflection, evaluation, or problem-solving)		
Gathering Information	Data during experimentation or observation		
	Selecting and/or organizing relevant data or information from other sources (emphasis on need for selection, not simple compilation)		
Critiquing Results or Conclusions	Evaluating logical, empirical, or conceptual consistency (may include consideration of implications; may include a look at quality of evidence for a conceptual model)		
	Critiquing experimental design, weighing experimental evidence, justifying ideas in light of such evidence.		

	Comparing alternative theories or theoretical frameworks		

Instructor actions to promote or model = I Student evidence = S		Time: **Method:** I	 S
Primary literature skills	Finding, reading and organizing primary literature; discussing use of primary literature and relevance to inquiry		
Verbal skills	Communication in science through writing or presentations		
Quantitative skills	Analyzing data: Organizing, representing, and analyzing data; use of various representations and analysis tools (Excel or stat. package). Statistical data analysis		
	Quantitative problem-solving and modeling (discusses, demonstrates, or refers to quantitative problem solving or using numerical models in science)		
Content	Field-specific bodies of knowledge; gives content information in any form		
	Field-specific cognitive skills (thinking/problem-solving skills specific to domain, e.g. Punnet square, free-body diagrams, medical procedures)		
	Field-specific lab skills		

3.3.2 Reliability of classroom observation rubric

The classroom observation rubric and its codes had been in development for several years prior to its use in this study. The classroom observation rubric was piloted across introductory science courses at three different institutions a year prior to this study and was refined in a series of debriefing sessions with education researchers throughout the year. During the year of this study, the observers achieved an inter-rater reliability of 84% when coding classroom events using the classroom observation rubric. Thus, the classroom observation rubric was considered to be a reliable instrument for observing classrooms and recording frequencies of classroom events. In frequencies of classroom events. In the Fall 2000 semester, 10 classes were observed in the primary case; 3 classes were observed in lecture 1 and 3 classes were observed in lecture 2 using this instrument.

3.3.3 In-depth pair sessions

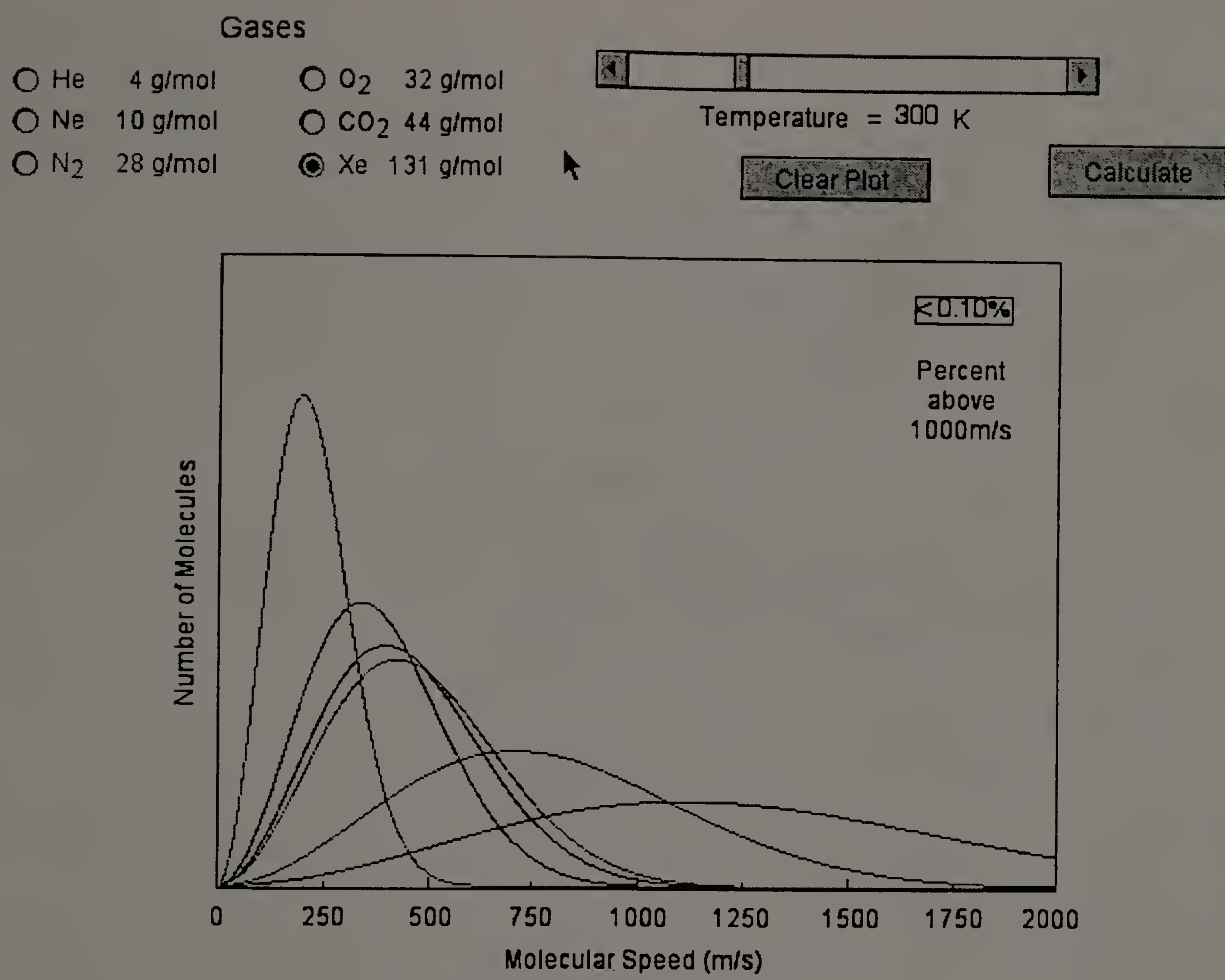
Peer discussion at the computer and discussion with their teacher was documented in the primary case during the classroom observations; however, the interaction between the student, the teacher, and the computer had been difficult to capture in great detail in the course of a typically dynamic classroom period in the primary case. The purpose of the student interviews was to capture and elaborate on students' responses to the primary case teacher's interventions and their learning trajectories in greater detail than the classroom observations would allow. A special interview protocol was designed to document students' learning pathways during instruction (Khan, 2001). In these in-depth sessions, the primary case teacher "taught a class" to a pair of students from the primary case, where the teacher, the students, and the interactive computer tools played the same roles that were observed during class, except students were prompted by an interviewer to "think out loud." The interviewer was the author, who had prior experience conducting focus groups and think aloud interviews with student pairs at computer terminals.

Twelve students or 6 student pairs were "taught a class" in this way mid-way through the class (over a third of the students enrolled in the primary case participated in the in-depth sessions). Student participants were selected based on their receptiveness to this interview and their schedules. Each student received a phone call and a request for informed consent to participate in the interviews in exchange for a $20 payment (Krueger, 1994) for their participation. During the in-depth pair session, a student pair was seated at a computer that had two mice with the primary case teacher teaching new material using 3 pre-selected interactive computer tools. Each session was tape recorded and video-taped with informed consent. Students who participated in the in-depth pair sessions also completed a pre-post test for conceptual understanding.

<u>The sequence of the in-depth pair sessions followed the general script:</u>

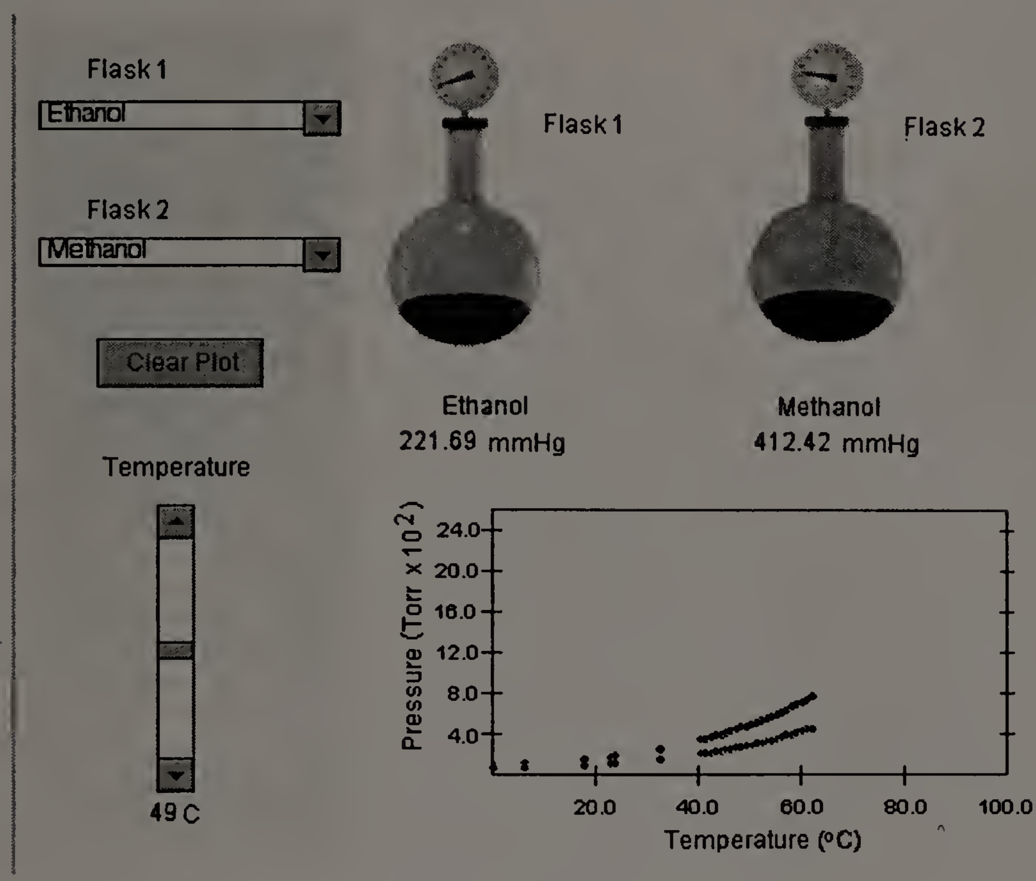
1. The primary case teacher provided a definition of Boltzmann's distribution.
2. The primary case teacher showed students how to use the Boltzmann distribution interactive computer tool and pointed out temperature and molecular speed as the important variables, using an example (O_2 at 300 K) as a sample data point. He also used an analogy of cars on a highway to further describe molecular speed.

GasPhase.dcr



3. The primary case teacher asked students to find a general relationship between temperature and molecular speed with the Boltzman distribution simulation (BZD).
4. Students generated a relationship with the Boltzman distribution simulation (BZD).
5. The primary case teacher asked students to explain this relationship.
6. The primary case teacher repeated steps 3- 5, for the relationship between different gas molecules of different molecular weights on molecular speed with the Boltzman distribution simulation (BZD).
7. The primary case teacher provided background information on vapor pressures.

8. The primary case teacher asked students to collect data on the effect of temperature on vapor pressure with the Equilibrium Vapor Pressure (VP) simulation.



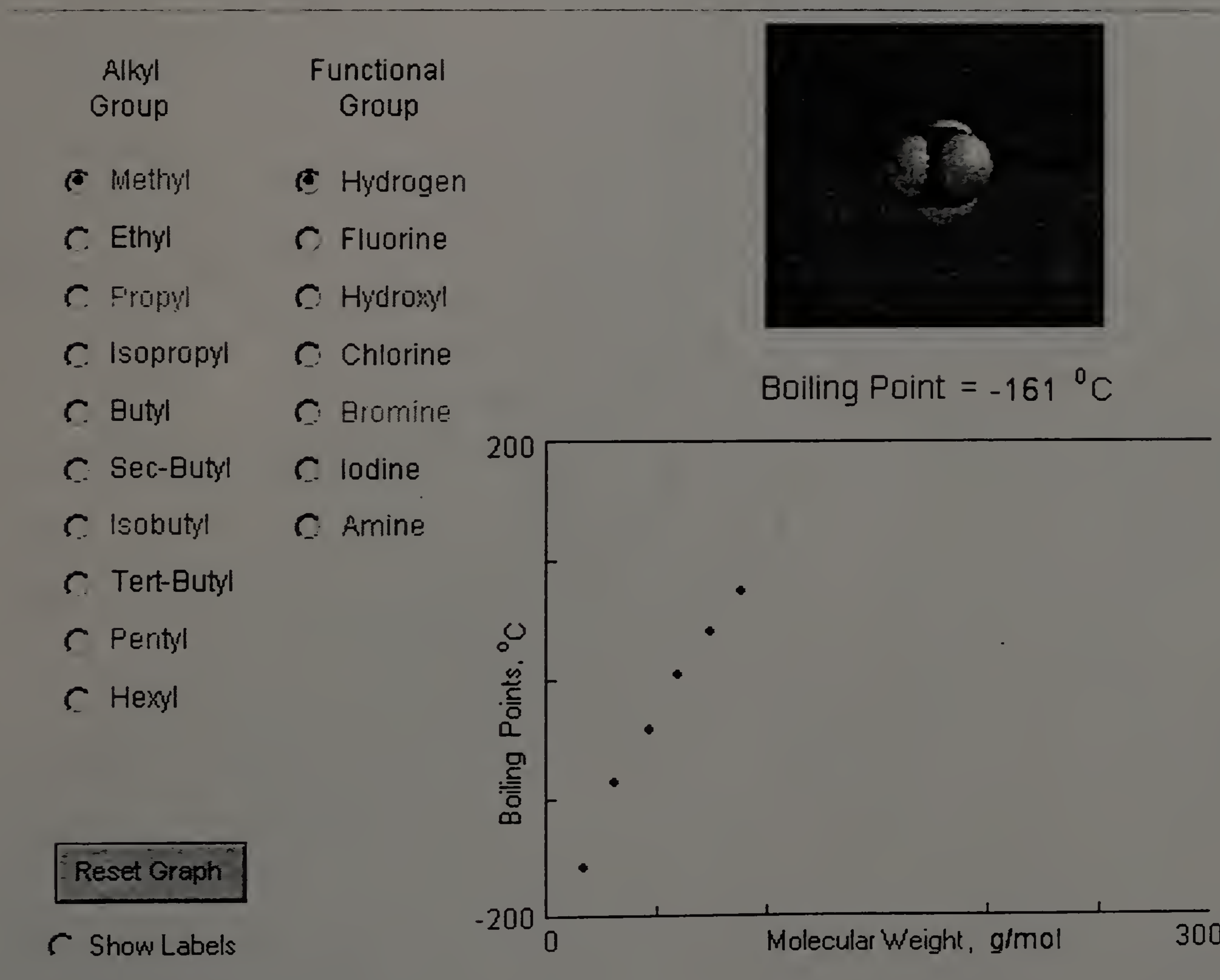
9. Students generated a relationship between temperature and vapor pressure using the VP simulation.

10. Students were asked to explain why vapor pressure increases with an increase in temperature.

11. Students followed a similar instructional cycle to generate a relationship on the effect of the kind of molecule on vapor pressure (at 760 mm Hg or boiling point).

12. The primary case teacher asked students to compile information with the Organic boiling points (BPTS) simulation.

13. Students compiled information with the BPTS simulation and encountered information that did not support students' initial relationship.



14. The primary case teacher asked students to construct an explanation that modifies the rule taking into account the disconfirming information.
15. The primary case teacher asked students to use modification of rule to predict the boiling points of two new compounds, ethanol and benzene.

3.4 Congruency

It was important for the in-depth pair sessions (Khan, 2001) to maintain as much congruency with the classroom as possible. The in-depth pair sessions made possible the detailed study of the critical interactions between the primary case teacher, the student, and the computer tools. It was hoped that the in-depth pair sessions could help elaborate on the learning that also characterized the larger classroom.

Table 8. Congruency between classroom and in-depth pair sessions.

Elements of instruction	Classroom	In-depth pair session
Teacher	Primary case teacher	Primary case teacher
Teacher's instructional strategy	Guided discovery approach	Guided discovery approach
Student numbers	26 students (small groups, whole class)	2 students (pairs)
Main role of the software	Provided information	Provided information
Interviewer role	Record observations only	Ask students to: Think out loud! Why did you click there? What are you thinking now? What are you doing now? Speak up!
Setting	Electronic classroom with 26 computers	Mini-classroom with a single computer that has 2 hand-held mice.

The primary case teacher reviewed the in-depth pair session protocol and believed that the structure of the in-depth pair session protocol was congruent with his classroom approach to instruction. While there were substantial differences in the setting and size of the in-depth pair sessions, the in-depth pair sessions maintained substantial similarities to roles of the primary case teacher, the students, and the computer in the classroom. In addition, the same approach to instruction and the same type of teacher activities and specific guidance strategies were observed in both situations. Thus, the teaching and learning episodes that emerged from the in-depth pair sessions were believed to be reasonably valid representations of the interventions and possible learning pathways and trajectories that characterized the teaching and learning in the primary case classroom.

3.5 Pre-post Chemistry Attitude (CAT) surveys

Pre and post Chemistry Attitude (CAT) surveys with a 5 point Likert scale were administered on-line before and after instruction in the three chemistry classes. The surveys were designed to gauge students' perceptions of their learning experiences in the class. The process of developing the survey began with a focus group in 1999. A focus group of students from the primary case provided a source of core issues to present later on as statements in the CAT survey to the larger group. The survey results were brought back to the focus groups and the primary case teacher for their elaboration and responses. In this way, the development of these surveys was reflexive, moving from classroom observations and interviews to classroom surveys in the primary case and back to the teacher or the students in the focus groups. For example, the survey statement "Peer discussion is valuable for my understanding of science topics" was included in the Spring 2000 survey only after a focus group discussion in Fall 1999. Each time, the survey statements were peer-reviewed by educators and scientists. This cycle of refinement of the surveys occurred twice in total (once per semester with two semesters of classroom observations before the current study).

Thus, the CAT surveys were piloted over a period of one year prior with trials to over 500 students in introductory chemistry and feedback from student groups.

Consequently, the CAT survey statements were believed to be a reliable reflection of core issues and major student perceptions in introductory chemistry.

3.6 Data collected

In total, the data collected were classroom observation notes from the 3 classes (primary case, lecture 1, and lecture 2), 16 classroom observation rubrics from the 3 classes, 6 in-depth pair session videotapes and audiotapes of student pairs in the primary case, 12 pre and 12 post concept tests, and 343 pre and post CAT surveys from the 3 classes.

Table 9. Data collection.

DATA	Primary case	Lecture 1	Lecture 2
Pre-Post survey	Yes	Yes	Yes
Classroom observations	Yes (10)*	Yes (3)	Yes (3)
In-depth sessions	Yes (6 pairs)	No	No
In-depth sessions pre-post tests of conceptual understanding	Yes	No	No

* In the pilot study, an additional 10 classroom observations of the primary case, a faculty interview with the primary case teacher, and 2 focus group interviews with 8 students from the primary case were reported (Khan, 2001).

3.7 Analysis

3.7.1 Quantitative data

The quantitative data was analyzed using SPSS statistical software. The quantitative data consisted of classroom observation data and CAT survey data. Frequencies of activities and processes were determined using the classroom observation notes and classroom observation rubrics.

The frequencies of activities and processes per class were calculated from the classroom observation notes and then compared with the same data in the contrasting cases using the classroom observation rubrics. A central pattern of instruction emerged from this analysis of classroom observation notes.

The classroom observation rubrics were coded according to categories of classroom activities using ranges, where 0 meant the activity was not observed within that designated portion of the classroom period; 1 meant the activity was observed 1-2x in that designated portion of the classroom period, 2 meant the activity was observed 3-5x in that designated portion of the classroom period, and 3 meant that the activity was observed greater than 5x in that designated portion of the classroom period.

The number of instances for each activity were totaled by hand, and checked against the ranges that had been determined earlier. An average number of instances was then determined over all of the lessons observed. Because the primary case had a twenty five minute longer lesson period than the Lecture 1 & 2 lesson periods, all of the primary case average instances per skill per lesson were multiplied by 0.67 to make the time equivalent with Lecture 1 and 2 lesson periods.

For example, the hand counts revealed that 30 instances of instructor actions to promote or model generating inquiry questions were observed in the primary case in a total of 10 classroom observations.

Table 10. Total instances of events in the primary case.

Instructor actions to promote or model = I **Student evidence = S**		**Time: Method:** I	S
Generating Ideas	Questions for or as a result of inquiry	30	
	Predictions (simple hypotheses) or rules concerning simple relationships between variables	12	11
	Experimental Designs or Tests		3
	Explanations or Conceptual Models (causal or mechanistic	20	19

	explanations – why or because. Could be done before or after testing, reflection, evaluation, or problem-solving)		

If the 30 instances of the activity were observed in a total of ten observations in the primary case, then the average number of instances was three per class in the primary case. In order to make time equivalent across all cases (primary case, lecture 1, and lecture 2), the 3 instances on average per classroom observation in the primary case was multiplied by 0.67 to take into account that the classroom periods in the primary case were longer than in the lecture classes. The resultant calculation of 3 x 0.67=2.01 was rounded to the nearest 0.05 and reported as: on average, 2 instances of generating inquiry questions were observed per classroom unit time period. Once the time period across cases was made equivalent, ratios between the average number of instances per class in the primary case and the lecture classes could be determined. These ratios would then allow some baseline comparisons about how often certain inquiry skills were occurring in each class.

The CAT surveys from the 3 classes and the test for conceptual understanding were subjected to statistical analysis. Frequencies, means, Chi-square, paired T-tests, and ANOVAs were performed on the data using SPSS statistical software.

3.7.2 Qualitative data

The qualitative data was analyzed using a constant comparative approach (Glaser & Strauss, 1967). Glaser and Strauss described the constant comparison method as following four distinct stages:

1.comparing incidents applicable to each category,

2.integrating categories and their properties,

3.delimiting the theory, and

4.writing the theory (Lincoln & Guba, 1985).

Thus, hypothesis generation (relationship discovery) began with the analysis of initial observations. This process underwent continuous refinement throughout the data collection and analysis process, continuously feeding back into the process of category coding and sub-coding. As events were constantly compared with previous events, new dimensions as well as new relationships were discovered.

The qualitative data consisted of classroom observation notes and in-depth pair session transcripts. The codes originally emerged from initial observations of the classroom and the observation rubric. Videotapes of the classroom and the codes were discussed in debriefing sessions with other educators and the primary case teacher to ensure trustworthiness. The codes were then applied to the transcripts from the in-depth pair sessions and analyzed using the constant comparative approach (Glaser & Strauss, 1967) described above. Where possible, the data was triangulated with the findings from the surveys to support emerging hypotheses.

Coding classroom observations. Classroom events in the three classes were initially coded according to the classroom observation rubric using the codes that were a part of the classroom observation rubric. Secondly, all instructor questions recorded in the classroom observation notes were further subdivided into two possible question types: content based questions or process based questions. Content based questions were questions from the teacher that asked students for factual, field specific information. Process based questions were considered to be questions from the teacher that asked students to generate ideas, gather information, critique results or conclusions, analyze primary literature, communicate through science writing and presentations, or analyze a quantitative problem. Administrative questions were excluded from both categories. The table below provides examples of teacher questions that were coded as either content questions or process questions.

Table 11. Two categories of teacher questions to students.

Content	Process
What does properties mean?	What would be the bond angle that you would predict for resonance structure 1, draws a cloud picture of ^{24}Mg and says what's wrong with this picture based on Coulomb's Law? resonance structure 2?
What makes a metal a metal and a non-metal a non-metal?	What is the reason why He is different from O_2?
What's the single distinguishing characteristic of all antibonding?	What will happen to number of collisions if I double the number of moles?
	What are the trends that occur as you increase temperature for the phases of the elements?

Administrative questions by the instructor, such as, "Any questions about the homework?" were excluded from coding and analysis.

Thirdly, classroom observation notes in the three classes were coded again to include all of the same in-depth pair session codes and sub-codes that are described more fully in the section below on in-depth pair sessions.

Coding the in-depth pair sessions. The in-depth pair sessions were tape recorded, transcribed and analyzed using a constant comparative method of analysis (Glaser & Strauss, 1967). Codes and sub-codes for the in-depth pair sessions transcripts were initially developed from three sources:

1. Vining case study (pilot study of classroom observations in Fall 1999; case report submitted Nov 2000).
2. Classroom observation rubric (developed in conjunction with the author at Hampshire College, MA, Spring 2000- Fall 2001).
3. Observation report (classroom observations Fall 2000; report submitted Jun 2001).

<u>**Codes in both the classroom observation rubric and the in-depth pair sessions.**</u>

The codes that were used in the classroom observation rubric and the in-depth pair sessions are reported below:

Table 12. Common codes.

Rubric code for both classroom observations and in-depth pair sessions		Name of code and sub-codes	
Generating Ideas	questions for or as a result of inquiry	g,m	
	predictions (simple hypotheses)	p	
	or rules concerning simple relationships between variables	g,m	sq
			quant
	experimental designs or tests	ex	
	explanations or conceptual models (causal or mechanistic explanations – why or because; could be done before or after testing, reflection, evaluation, or problem-solving)	e sum	
Gathering Information	data during experimentation or observation		
	selecting and/or organizing relevant data or information from other sources (emphasis on need for selection, not simple compilation)		
Critiquing Results or Conclusions	evaluating logical, empirical, or conceptual consistency (may include consideration of implications; may include a look at quality of evidence for a conceptual model)	lc	
		ec	
		cc	
	critiquing experimental design, weighing experimental evidence, justifying ideas in light of such evidence.	we	
	comparing alternative theories or theoretical frameworks		

Classroom observation rubric code		In-depth pair session codes and sub-codes
Primary literature skills	Finding, reading and organizing primary literature; discussing use of primary literature and relevance to inquiry	
Verbal skills	Communication in science through writing or presentations	
Quantitative skills	Analyzing data: Organizing, representing, and analyzing data; use of various representations and analysis tools (Excel or stat. package). Statistical data analysis	
	Quantitative problem-solving and modeling (discusses, demonstrates, or refers to quantitative problem solving or using numerical models in science)	quant
Content	Field-specific bodies of knowledge; gives content information in any form	c a sum
	Field-specific cognitive skills (thinking/problem-solving skills specific to domain, e.g. Punnet square, free-body diagrams, medical procedures)	ps
	Field-specific lab skills	

<u>**In-depth pair session codes**</u>. Most of the in-depth pair session codes were the same as the classroom observation rubric codes by category; however, there were several codes in the classroom observation rubric that were not included in the in-depth pair sessions, and there were several codes in the classroom observation rubric that were sub-divided into sub-codes in the in-depth pair sessions. The reason for the differences were because the classroom observation rubric coded for science process activities; however, there was a need to augment these classroom observation codes with more specific codes for instructional strategies and learning processes in order to more precisely characterize teaching and learning in this study. These differences will be listed in

the next two sections; followed by more detailed definitions of codes, their criteria, and examples from the classroom or in-depth pair sessions.

Codes in the classroom observation rubric but not in the in-depth pair sessions.

The codes that were used in the classroom observation rubric but were not used in the in-depth pair sessions included data during experimentation or observation or field-specific lab skills. These two rubric codes were not used in the in-depth pair sessions since students were not going to be collecting raw data or conducting an experiment in the in-depth pair sessions. In addition, students were not going to find, read, or organize primary literature; discuss the use of primary literature and relevance to inquiry, communicate in science through writing or presentations, or analyze data using Excel or a statistical package with the students according to the in-depth pair session protocol that was prepared.

Sub-codes that were applied to the in-depth pair sessions.

Table 13. Sub-codes.

Classroom Observation rubric and in-depth pair session Categories	Sub-code	Name of sub-code
Generate ideas	**Quant**	Quantitative relationship
	Sq	Semi quantitative relationship
Evaluate	**Ec**	Empirical consistency
	Lc	Logical consistency
	cc	Conceptual consistency

Additional codes. The following codes were not mutually exclusive to a single category: summarize, surprise, compare, increments, simulation, extreme case. That is, students could have expressed surprise while also generating ideas or analyzing data. Teachers could have summarized the content or summarized an explanation. Students could have used the simulation to generate ideas, evaluate ideas, or solve quantitative problems. Thus, these codes were not mutually exclusive to a single category, but many of them could be applied to more than three categories. These additional codes were applied to the classroom observation notes and the in-depth pair sessions.

Gathering information code. This code was not coded for in the classroom observation notes since it was decided that gathering information was applied to the context of gathering raw data from laboratory or field experimentation or from real-time databases or primary literature. The experiment-based gathering information was not observed within the classroom. Thus, gathering information was not coded during the classroom observations.

Rather, students were considered to be "compiling information" when they used the computer simulations in the primary case. There was a need to classify the type of information that students were working with in the primary case, so an additional category, called compiling information (d) was created. This code was applied to the in-depth pair sessions only, where the type of information was subdivided into two categories: disconfirming information (de) or confirming information (ce). In addition, if students were observed changing variables in the simulation in order to compile different kinds of information, the code was referred to as (v).

3.7.3 Code criteria

Mutual exclusivity. In classroom observation, a segment of the class was defined by an instructional method, which extended over some period of time. During a time segment, multiple inquiry codes could potentially be assigned. Thus, the inquiry codes were not mutually exclusive within time segments defined by instructional method. In the in-depth pair sessions, however, codes were applied to individual utterances. At the level of an utterance, the inquiry codes were mutually exclusive.

Code criterion with examples. The criterion for each code is described below in Table 14. The codes in the table are not presented in any particular order, but they generally include the process codes in the classroom observation rubric and the process and instruction codes applied to the in-depth pair sessions. The underlined text describes the kind of statement within a transcript that would satisfy the particular code criterion in question. Only the code is underlined within each example.

Table 14. In-depth pair session codes with examples.

Code	Criteria	Example
g	**Generate** ideas: Evidence of instructor actions to promote or model, or student evidence of, generating relationships between 2 or more variables based on information gathered.	Ln 211. T So why don't you now look at the different molecules and see what effect having different gas molecules has as opposed to having just different temperatures? So keep the temperature. S2 Constant temperature. *(In-depth pair session 1)* Eg. T Refers to a list on the board of bond lengths between single, double, and triple bonded carbons and asks students what do they see. S10 More bonds (as bond order goes up), the bond length decreases. *(Classroom observation Lesson 4.01)*
e	**Explanations:** Evidence of instructor actions to promote or model, or student evidence of, explanations or conceptual models (causal or mechanistic explanations-why or because. Could be done before or after testing, reflection, evaluation, or problem-solving)	Ln 703. T Okay so I have another question then. So as the temperature goes up, vapor pressure goes up you said. Come up with an explanation for that. Why as the temperature goes up does the vapor temperature go up? *(In-depth pair session 1)* Ln 585. S2 It's liquid so it's going to act a little bit differently than gas, but I mean it's pieces of the same, it's very similar, so as you increase temperature, the molecules are going to bounce off each other more. They get closer to the boiling point therefore more and more molecules are actually I guess at the boiling point. S1 Yeah, but how do we relate that to

Code	Criteria	Example
		pressure? Like I could get that far but. S2 Well I know, but then, okay, <u>as we increase to boiling, the temperature, more and more molecules are above the boiling point so therefore more and more molecules go out of the liquid phase. Rise up into the vapor phase and then as you get more molecules in the vapor phase it becomes denser and pressure increases.</u> *(In-depth pair session 3)*
extr	**Extreme case**: Evidence of instructor actions to promote or model, or student evidence of, the examination of an extreme case that may or may not be relative to a series of cases.	T Think about how you can make <u>the most polar bond.</u> What's the most polar bond you have found so far? S1 Chlorine and aluminum. <u>Cl is the most electronegative or polar.</u> *(Classroom observation Lesson 5.01)* Ln 159. T Now, looking at this, do you think that that's a linear relationship-that that's directly proportional? That is, is speed is directly proportional to temperature? If you double the temperature, will the speed double? S1 Probably not. T Talk about it. S1 You'd probably reach a certain point where the hotter it is, it may not go as fast as it had done originally. You know what I mean? Like, when you first start heating something up, it may not move as fast, because <u>when you heat to a certain point where it moves real fast</u> and then it will plateau out again. I forget what that's called. Um, some sort of exponential-it plateaus, though. You know what I'm talking about? Ln 172. S2 Mmm. I don't know. S1 Like, it will continue to go up. S2 Yeah, I know what you're talking about with the shape. Ln 185. S1 Well, it has to do that at a certain point, because <u>molecules can't necessarily travel faster than the speed</u> of light, you know? Because, there's a definite speed point that something can reach at. So, I don't want to. S1 I don't know, maybe it's proportional under relatively normal conditions? But, I don't think it's proportional in the grand scheme of things. *(In-depth pair session 6)*
v	**Variables:** Evidence of instructor actions to promote or model, or student evidence of, selecting, defining or controlling	Ln 245. S2 Well yeah. <u>It depends on what you're varying. If you vary the temperature or if you vary the molecular size. As you vary molecular size, the greater the molecular size, the greater the mass with same temperature acting upon it , you're going to get less and less</u>

Code	Criteria	Example
	variables in an effort to compile more information.	movement. Whereas if you have greater temperature on a given mass, you're going to get more movement. T Okay, so discuss this for a second. So the thing you just have one temperature and you looked at different molecules, was the force changing between those? Ln 256. S2 Well force is the energy. No it doesn't. S1 It's constant here. S2 Yeah the variable in that case is mass. I forget the equation for force. It's like. S1 Yeah, the only thing that is changing is mass. You can't compare temperature right now. *(In-depth pair session 3)* Ln 1149. T So what we want to do is, we want to start out, we want to use this to see if your trend there actually works for more than say, two compounds. So the first thing to do would be to keep this as hydrogen and look at the relationship between molecular weight. This will make a graph for you to the boiling point and molecular weight, then you vary how large this alkyl group is. How big the molecule is and it shows you a picture of the molecule as you go along. So go ahead and do that. You can hold onto this and see if it seems to, if your rule seems to hold. *(In-depth pair session 3)*
a	**Analogy:** Evidence of instructor actions to promote or model, or student evidence of, using an analogy (key words: like, as if)	Ln 25. T So what happens is you can do this- this is kind of like going out and measuring how fast cars are on the highway. So what you can do is , you can go out and you could stand next to the highway, and you measure how fast cars are going by for a couple hours, and write down 53, 58, whatever, and when you get done, you could make a plot of how many cars were going at each increment of miles per hour. And you would see that not very many were going at 40 miles an hour, and a bunch were going 60 miles an hour, and a whole lot were going 70, and not many were going 90. *(In-depth pair session 6)* Ln 455. S1 Well it's the same if you have like a group of people, okay like sumo wrestlers yeah. I Sumo wrestlers heh. (laughter) S1 They are very slow because they have a large mass, whereas, I don't know like marathon runners. Okay, they tend to be very slow and then fast (garbled). It's like that's how

Code	Criteria	Example
		they are. (laughter) S2 Yeah exactly. I All right. Ln 468. T When a marathon runner runs or when a sumo wrestler runs, are they expending the same amount of energy or not given that they are running at different speeds? Like you said. S1 Umm. T In a real sense. (laughter) S2 Ahh. S1 Unnno. Ln 480. S2 Well I mean the marathon runner doesn't have to use as much energy to move himself. S1 Yeah. S2 As the sumo wrestler, so. T But what about the fact that the marathon runner is running faster? S2 Ahh. S1 Well okay then if the marathon runner was running faster, then he'd be giving off more energy as he runs, whereas it's vise versa for the sumo wrestler. Ln 493. T So the sumo wrestler. S1 The sumo wrestler may be trying harder, but he's not letting off as much energy because he has a greater mass. T But isn't the fact that the sumo wrestler has to move more mass around make him expend more energy even though? S2 It kind of equals itself out. T He's moving slower. Ln 506. S2 In the amount of energy that is used but not in the actual speed produced. Ln 509. T Okay, so what [you] are saying, that the sumo wrestler uses [an] equal amount of energy because the marathon runner is running faster but it's easier to run because. S2 Right. S1 Uh huh. T They're skinny versus sumo wrestler is running slow but expect more energy per mile per hour for instance. S2 Right. T Okay, I think that's what we're kind of saying about why the mass, as mass goes up speed goes down. Ln 530. S2 As the mass of a molecule goes up, it's harder, it takes more energy for it to move faster, so it doesn't go as fast at the same temperature. *(In-depth pair session 1)*

Code	Criteria	Example
d	**Data:** Evidence of instructor actions to promoteor model, or student evidence of, compiling empirical information.	Ln 964. T The next thing we're going to do is we're going to look at an easier way to quantify the loss of molecules as a measure of this, and that is boiling point. And boiling point is the spot-if you take this curve-at the point where vapor pressure crosses one atmosphere on the y-axis, that temperature is the boiling point. So the place where one atmosphere is equal to 760 mm of mercury. Why don't you click on these, and it will go up in one-degree increments? Find out the place where each of these crosses 760, and figure out what the boiling points for methanol and ethanol are [referring to the vapor pressure simulation]. Ln 971. S1 What are you looking at, methanol [referring to the graph of vapor pressures on the simulation]? S2 That would be a methanol. S1 Okay, just making sure. There, it's somewhere between. S2 64 and 65? *(In-depth pair session 6)*
p	**Prediction:** Evidence of instructor actions to promote or model, or student evidence of, expectation with regards to a relationship between or among variables.	Ln 103. T Okay so the first thing we want to do is we want to think about what will happen with temperature. If we change the temperature, what's going to happen to that curve and what I would like you to do is to first, before we actually do anything, is to predict what you think the curve will look like. So talk about this for a minute and then draw down what you think the curves will look like if we increase the temperature by a bunch. If we increase the temperature what will that curve, what will the new curve look like compared to that curve? So talk about it and do that. Ln 120. S1 What do you think? S2 I think it'll move over and be higher, since your going to go faster that way. I mean their speeds going to increase, but I think the molecules will probably stay the same because it's the same. Okay what do you think? S1 I'm thinking that it's going to like flatten out, like it won't be as high but it'll be longer. Ln 130. S2 Why? S1 I don't know I just [do]. It just seems like. S2 So the number of molecules will decrease? S1 Well, like the peak would decrease. But I mean it would be the same amount of like matter. So it would be the same number of molecules but it would. It would just have a higher average but it would still be, there would

Code	Criteria	Example
		still exist--the probability of a molecule moving at, you know, very, very slow speeds. You know because it doesn't really make sense that like when you increase the temperature, like a molecule couldn't move at a speed of say like 0. A molecule can't, you know there's always a probability of like a molecule staying still, just because I don't know. It makes sense. S2 Okay. *(In-depth pair session 4)*
cc	**Conceptual consistency:** Evidence of instructor actions to promote or model, or student evidence of, evaluating the consistency of the theory across models. For example, the theory that like charges repel and opposite charges attract does not hold for the atomic model.	Eg. T Draws a cloud picture of ^{24}Mg and says what's wrong with this picture [model] based on Coulomb's Law? S1 Why don't electrons pull into the protons? S2 Is the distance between the electron cloud and nucleus set? S1 We learned it as rings, remember? T What doesn't make sense? S6 Some electrons should be at different places like a p orbital. S7 Why don't electrons collapse into the nucleus? T Electrons are always trying to get closer to the nuclei. Always. S8 What is between the cloud and the nucleus? T Mostly a vacuum. Another glaring problem! S9 Why do all the protons stick together in the nucleus? T What holds the nucleus together? S10 Strong force. T The strong force operates only at close distances unlike electrostatic forces, that works at long distances, keeping protons together. *(Classroom observation 2.01)*
ec	**Empirical consistency:** Evidence of instructor actions to promote or model, or student evidence of, evaluating a quantitative or semi-quantitative relationship (increase, decrease, proportionality); relative to a set of empirical observations (observation 1,2,3).	Ln 1264. S1 So, hydroxyl and fluorine are all pretty much the same weight, but you can just compare the electronegativity and see which ones are more polar, and I'm guessing that hydroxyl's more polar because it has a higher boiling point than fluorine or amine. T Okay. Ignoring the hydroxyl and amine, does the same trend that you saw for the other things more or less hold up? S1, S2 Yeah. Ln 1273. T So then, the things to explain are the amine and the hydroxyl. So you're saying that they're at a higher boiling point therefore they must. S1 Be more polar. T It's obviously not a weight thing going on.

Code	Criteria	Example
		So why do you think they're more polar? S1 Because they have a higher boiling point at the same weight. T Okay. But, I'm sorry. Come up with a,-now that you know they're more polar. S1 They have a higher electronegativity. T Okay. So, do you have the periodic table there? S2 Uh huh. T Look at the electronegativities of the atoms. [students describe what electronegativity means to each other]. Ln 1316. T Why don't you compare like fluorine-the things that are attached to the carbons are fluorine and what else? Ln 1319. S2 Oxygen and nitrogen. T Okay. So why don't you compare those? S2 So the electronegativity goes to each of these because carbon is only 2.5. S1 Yeah. S2 So. S1 Fluorine should actually be more electronegative, because it has a higher electronegativity. It should be more negative, I mean, more polar. S2 Yeah. But, these all get the negatives, because. Ln 1334. S1 These are actually supposed to be more electronegative, according to this-uh, more polar. That's what we were saying. S2 Yeah. I think what we were saying is right. T What are you saying? S1 So we were saying that, like, hydroxyl and amine should be more polar when those are attached, but according to this Ln 1344. T I think you said they appear to be more polar. S1 Appear to be more polar. Yeah. But according to this [referring to data from periodic table] it's not going to be more polar. S2 Right. T Because, what on the chart [periodic table] is telling you that? S2 Fluorine should have the highest boiling point, if that was Ln 1354. T Because it has the highest electronegativity? S1 S2 Right. *(In-depth pair session 5)*

Code	Criteria	Example
lc	**Logical consistency:** Evidence of instructor actions to promote or model, or student evidence of, evaluating the consistency of the rule (if, then) under different hypothetical conditions	Ln 199. T Say there was just one molecule. If it was just one molecule and the temperature, the temperature went up. Would anything happen? So there couldn't be any collisions. Would the molecule go faster or slower or not change if the temperature went up? S1 If we stick to our original theory, then I guess it wouldn't change. S2 That's right. S1 There'd be no collision, so. T Okay, so why is the molecule, so if you think about it in terms of a single molecule and you raise the temperature up, why would they bounce of each other more quickly or more often, if each individual molecules isn't going faster? Ln 215. S2 Because heat (click). S1 Because I guess more heat would create more pressure. S2 Or energy. It like, it would give them the ability to, I'm not really sure why that actual. T I was just thinking about what you said that at a higher temperature, they would bounce off each other more, and so I'm trying to think about if individual molecules don't change their speed, how could they bounce off each other more at one temperature versus another temperature, if the individual molecules weren't going faster? Ln 228. S1 Okay we agreed that the collisions were causing pressure and not necessarily a change in the speed, so maybe if heat did increase the speed of a single molecule. S2 So we could say that heat does increase the speed of each molecule and then they also bounce off each other if there's a lot of them together and that would make them go even faster. S1 And that is why heat and pressure are related and heat and speed are related. Ln 251. T So they do collide more with each other and with the walls, but it's the collision with the wall that actually causes an increase in pressure, not collisions with each other. So the increase in this curve is that the individual molecules are going faster as temperature goes up, so because they have more energy. So more energy makes things go faster. Ln 265. S2 I was thinking of that they would have to collide with walls because I was saying

Code	Criteria	Example
		that the pressure couldn't increase if there were no walls at all. So I guess I would have made that conclusion eventually in some fashion. *(In-depth pair session 2)*
sum	**Summarize:** Evidence of instructor actions to promote or model, or student evidence of, summarizing a relationship or a set of relationships.	Ln 595. T <u>So as temperature goes up the kinetic energy goes up and molecules move faster. At a particular temperature heavier things move more slowly, lighter things move more quickly, so that's what we've learned here</u>. *(In-depth pair session 1)* Ln 752. S2 Oh and then he said that the material that the box is made of to begin with, the molecules because of the heat are vibrating against each other so when that one molecule bounces on that one it gets some of that energy from the vibration. T So a gas molecule can get energy from the molecules that are relatively stationary in the box? S2 Yeah. I just agree with him. (laugh) I don't have a set idea. Ln 761. T That really is the way it works. <u>The molecules, like he said, vibrate in the box and the energy from those vibrations actually transfers energy to the gas molecule and that's how we heat up a sample. Okay I'm going to leave this area now and go to another area.</u> *(In-depth pair session 4)*
s	**Surprise:** Evidence of instructor or student expression of surprise or disbelief.	Ln 1394. S1 <u>Why is amino over here?</u> (click) <u>I think it should be this way. Over here somewhere.</u> I Why do you think it should be over there somewhere? S1 Well because it's [amino] heavier than iodine and iodine is here, so it just seems like, if it was supposed to follow that trend it would be over there. S2 You're right, that wouldn't be. S1 It's over here. *(In-depth pair session 2)*
c	**Content:**	T <u>The strong force operates only at close</u>

Code	Criteria	Example
	Field-specific bodies of knowledge; instructor or student gives content information in any form.	distances unlike electrostatic forces, what works at long distances, keeping protons together. *(Classroom observation 2.01)* S6 In polar molecules, not all 3 are the same (referring to central atom and two adjoining atoms). T Different electronegativities will lead to different length dipoles. *(Classroom observation 5.01)*
ex	**Experimental design:** Evidence of instructor actions to promote or model, or student evidence of, designing a new test or considering methods of testing.	Ln 1119. T Okay, so now what else could we do? What else should we study? S1 We could do another functional group just to be sure, but we. Ln 1230. S1 (click) S2 Exactly the same. S1 Exactly the same. Ln 1247. T Okay so what other study could you then do? S1 Umm. T So that's the chlorine line and the other one over there is the iodine line. S1 Uh, huh. S2 Yup. S1 We could try it without a functional group at all and you'd have to have one. T That's a good idea and actually that's the way people think about it. That's what hydrogen is, hydrogen is actually not a real functional group. *(In-depth pair session 2)* Ln 1222. T Okay, so what could we do to test what the effects would be of the polarity? S1 You can test it? T Yeah. S1 You can, well just comparing these, you can tell they all have the same like mass, so that you can see that some are more polar than the other. T Yeah. Okay, tell me something better than that. Ln 1234. S1 Like a test? T Yeah. What else can we do here to test the effects of polarity? S1 You can choose a different functional group and see. S2 Yeah, like all chlorine, bromine and iodine are all pretty electronegative, too. Ln 1243. T Well, actually that's not true. Iodine is not very electronegative. Iodine has an electronegativity of 2.5, which is the same as carbon. Whereas, fluorine has 4.0. They're really vastly different. *(In-depth pair session 5)*

<table>
<tr><th>Code</th><th>Criteria</th><th>Example</th></tr>
<tr><td>de</td><td>Discrepant information:
Evidence of students encountering anomalous information in reference to what they already know.</td><td>S2 Yeah I mean, the amine and the hydroxyl ones seem somewhat. Oh according to the graph it looks like they, <u>all three of those should have the same molecular weight, but the boiling points are all different.</u> (In-depth pair session 1)

<u>S2 It's the only one [gesturing towards hydroxyl point on graph] that's not in.</u>
<u>S1 In the line [gesturing towards point on graph]. It's not linear.</u> It's sort of higher.
S2 Yeah, it's.
I Hydroxyl?
S1 Uh, huh.
S2 <u>It stands out. For some reason.</u>
S1 <u>It doesn't follow the trend.</u>
S2 <u>It doesn't follow the trend.</u> (In-depth pair session 2)</td></tr>
<tr><td>ce</td><td>Confirming information:
Evidence of students encountering information that confirms what they already know.</td><td>Ln 1106. T So, go ahead and adjust what the alkyl group is, and look at what you see [students use boiling point simulation].
S2 So that pretty much [referring to the information in the simulation].
S1 Yeah, <u>that's just like we said</u>--the higher the molecular weight, the higher the boiling point [referring to the graph in the boiling point simulation]. (In-depth pair session 5)</td></tr>
<tr><td>ps</td><td>Problem solving strategy: Evidence of instructor actions to promote a general heuristic (work back from the data) or a field specific strategy to solve a problem (think of an individual molecule).</td><td>Ln 222. T I was just thinking about what you said that at a higher temperature, they would bounce off each other more, and so I'm trying to <u>think about if individual molecules don't change their speed how could they bounce off each other more, at one temperature versus another temperature, if the individual molecules weren't going faster?</u> (In-depth pair session 2)</td></tr>
<tr><td>com</td><td>Compare:
Evidence of instructor actions to promote, or student evidence of, making a comparison between data.</td><td>S1 <u>Well you can see it if you choose the lightest one and it can go the fastest and more of it can go the fastest, compared to Xe [the heaviest molecule] which is only, it's stuck at 250 Kelvin or.</u>
Ln 201. S1 <u>That one [pointing to He] can go the farthest or the fastest and most of them can go</u>, you know what I, like.
T So.
I Go on.
S1 <u>Yes and so Xe is compared to this one.</u> It's all stuck behind a number. It <u>doesn't go that fast.</u> (In-depth pair session 3)

<u>S2 Then how come they over lap at some</u></td></tr>
</table>

Code	Criteria	Example
		points [referring to overlapping datapoints of four isomers on the molecular weight vs. boiling point graph in the boiling point simulation]? T The reason that some of them are overlapping is that some of these things have the same molecular weight, so what happens is there's three of them. There's butyl, isobutyl and tercbutyl, so here's the four carbons, but you can actually make the carbons (garbled), that are just the butyl. Isobutyl is just there's a carbon branch and then there's two other one's there's propyl and isopropyl. They are different shapes but the same overall molecular weight, and so it looks like these are all those butyl's there and I think the two propyl's are there. So does it look like the shape is playing a big role? S1 No, which discredits my whole thing. (laugh) I How does it discredit your whole thing? S1 Well because I was saying that it's like interaction. Like I was thinking it was the interaction of like where the dipoles are where the partial charges are. Whereas like if it's just molecular weight, then that different formations have the same, where as like in my thing if it [isomer] had a partial charge sticking out somewhere, even though I had the same molecular weight, it would have a lower vapor pressure. (*In-depth pair session 3)*
sim	**Simulation:** Evidence of instructor actions to promote, or student evidence of, making a direct reference to the simulation.	Ln 32. T Just click on calculate [referring to the BZD simulation]. So this is a Boltzmann distribution for oxygen O_2 at 300 Kelvin, so what it does [referring to the simulation] is it shows a plot that looks something like this. And so what that means, what this is, is a plot of how many molecules are going different speeds. (*In-depth pair session 2)*
m	**Modify:** Evidence of instructor actions to promote or model, or student evidence of, changing the original relationship.	Ln 2096. T So now I want to go back to the big picture. The big picture was earlier on, for most things we saw the heavier they get the higher the boiling point. And now do you want to modify that rule that it was after our first thing, the rule was boiling point depends on how heavy it is. Do you want to modify that rule? I Like you had come up with the relationship that. S1 Right, right, right. Ln 2106. T You're writing the text book and

Code	Criteria	Example
		you're up to the section of the text book that's what controls boiling point and you write 'boiling point it depends on how heavy the thing is.' The greater the molecular weight the higher the boiling point. I Which is what you said right? S2 Yes. T And which for lots of things work. Do you want to write anything else in your little textbook or [do] you want to end that there? Ln 2118. S2 I think it's probably a combination of what we both said. It depends on the weight and the attractive forces between the molecules. I And is one more important than the other? S1 Well. S2 I think maybe that the functional group has the bigger role more so than the weight. I In other words the attractive forces. S2 Yeah. (*In-depth pair session 4).*
incr	**Incremental values**: Evidence of instructor actions to promote or model, or student evidence of, the generation of a semi-quantitative or a quantitative relationship using incremental values.	T Try to double the distance and see what happens. S2 It's d^2. T Now look closely between the magnitude of charges and what the force is. S3 It changes in increments. T What do you see? S4 When the charge goes from –1 to –2, the force doubles. T From –2 to –3, does it double again? Go on and make changes to the simulation. T It is going up in multiples of 1.4. Therefore force is directly proportional to charge 1 times charge 2 over d^2 (written as an equation on the board). The larger charges, the stronger the force. The larger the distance, the weaker the force. (*Classroom observation Lesson 2.01)* Ln 388. T What I want to do is, I want to look at the speed temperature thing again in a little more detail. So go back and make a graph at 300 and 600. Actually you have to do it for one of the heavier molecules. S1 Okay. T Yeah I want it to be exactly double like 300, 600. Okay so now look at that fairly carefully and think about whether or not you think the speed and the temperature might be directly proportional or it might be proportional in some kind of other thing, like there might be that

Code	Criteria	Example
		temperature is proportional to the log of the speed or the square of the speed. My questions is you can't figure that out per se, <u>but what I 'm really curious is if you think it really is directly proportional, so if you double the temperature do you double the speed? If you triple the temperature do you triple the speed? Is it directly proportional or is it less sensitive or more sensitive?</u> I'm thinking in terms of speed on temperature. Ln 406. S1 Can we go back to 600? That's 51%. S2 This over here? What do you want me to do? S1 Can we go back to the 600, do we just click on this? S2 You can change it. (click) S1 9.4% and the other one was .51, so is that about. Is that what that's for? T Yeah that's actually not what that's for. Ln 426. S1 Oh okay. S2 Okay. We'll just look at this maximum point here is about. S1 400. S2 About 350-400. S1 Uh, huh. S2 And this one here. Okay what we're looking at is where the maximum points of these curves are. S1 Uh, huh. S2 And we can tell that this one is about 350 to 400. And this one here is about. S1 5,600? S2 <u>About 600. And we know that this curve represents the 300 degrees and this one represents the 600 degrees, so if this was really 300 like about 300 and this one's really about 600. I would guess that they are directly proportional</u>. Ln 451. I What do you think? S1 This one seems, we were saying before this one seems like it's more like 350 to 400. S2 Yeah. S1 So. <u>S2 It seems a little bit more, yeah they're not directly.</u> <u>S1 Yeah they're not directly proportional. They're close though.</u> *(In-depth pair session 2)*

Examples of coding.

Coding	In-depth pair session transcript
Generate ideas Variables Simulation (Asks students to generate a relationship from simulation; delineates variables)	Ln 45. T So what we want to do is we want to start out by exploring the effects of temperature on what these distributions are, these distribution speeds are and then we're going to look at the nature of the molecules and see what happens when we change what the molecules are. So why don't you spend done time first exploring and it's the same system as in class where there's two mice explore what happens when temperature changes and see what occurs?
Simulation Variables Compare Data Generate ideas Analogy	Ln 57. S2 Just temperature reading. Well I was thinking that like molecular speed is the same thing as, well speed is basically equivalent to energy and heat and therefore the middle of the graph. The median or whatever is greater than the one that is at lower temperatures it seems like. For the new one it would be somewhere around 500 whereas the lowest one somewhere around 400 to 450 or so. S1 Yeah, I think it's just showing as temperature increases the more molecules can go up past the molecular speed there. It just keeps increasing. T Okay so as temperature goes up, what happens to the distribution of speeds? S1 There's more distribution and more higher speed it can go to. T Okay so they go at higher speed and what do you mean by more distribution? Ln 76. S1 Well because this one's at a big point here and most of them are going like the cars would be going. Most of them are at like between 60, but here it would be going between 40 and 80. You know. T Okay, yeah. It's like a wider distribution. S1 Yeah. S2 That's a good point I didn't notice that. (In-depth pair session 3)

Explanation: Explanatory model construction began with a discussion by students of the mechanism of molecular motion as temperature increases.

Ln 572. T Why does vapor pressure go up as temperature goes up?
[tells students to talk with each other]
Ln 585. S2 It's liquid so it's going to act a little bit differently than gas, but I mean it's pieces of the same-very similar, so as you increase temperature, the molecules are going to bounce off each other more. They get closer to the boiling point therefore more and more molecules are actually I guess at the boiling point.
S1 Yeah but how do we relate that to pressure? Like I could get that far but.
S2 Well I know but then okay as we increase boiling, the temperature more and more molecules are above the boiling point so therefore more and more molecules go out of the liquid phase, and rise up into the vapor phase, and then as you get more molecules in the vapor phase it becomes denser and pressure increases.

Evaluation, empirical consistency

Simulation (vapor pressure)

Students use data from the graph to search for empirical support. They read graphs and draw their own graphs. Using the graph of vp & their understanding of the distribution of molecules from the BZD plot, students attempt to come to an agreement of when vapor pressure starts as temperature is increased.

Ln 600. S1 No but boiling point, when you go to boiling point that's not when the first vapor pressure starts I don't think. Like there's already stuff before so you can't say that when the temperature increases then all the pressure starts. You know what I'm saying?
S2 Well I understand what you're saying about the thing but I mean this, the graphs we were looking at before were of liquids, or of gases.
S1 Gas yeah.
S2 But I'm thinking that the, I mean it's really a close correlation. I mean the graph probably looks different or whatever, but like I was saying here like you know, this is if you have water at 70 degrees.
S1 Uh, huh.
Ln 616. S2 And this is the graph of the, of all the temperatures, of all the molecular speeds of that water. It's not all going to be at like 70 degrees, it's not going to be of like some huge spike of like at 70 and nothing anywhere else. You know you got some down here at 30 degrees and then you got some over here well you got a 130, so this portion of the graph that's above 100 which means 130 and it gets less and less. This portion of the graph is, makes up the vapor portion of this non-vapor pressure measuring thing, so therefore as you move this median or if you increase the temperature of the umm.
S1 System.
S2 System. This moves to the right and let's say it gets here, let's say it's at 85, you going to get this, might move up to this is the greater portion of the graph past 100.
S1 Uh, huh.
Ln 634. S2 Therefore greater portion, greater amount

of molecules for a given volume. The volumes aren't changing but you're putting more molecules in there therefore pressure goes up.
S1 Yeah. I understand that totally but I'm just saying that you're putting this spot at 100 degrees. I don't know if I'm wrong, probably I am, but it's just the whole thing will. <u>Let's say you have 100 degrees as one, the pressure and the vapor pressure starting and this is the only thing that corresponds to the pressure here after a 100. That's what you're saying. After 100 degrees Celsius is when it boils water. Water boils and that's when the vapor pressure starts. Is that what you're saying?</u>
<u>S2 Starts?</u>
S1 Like.
Ln 651. S2 Let's say you know this is 30 degrees. Okay right and over here. Okay then right here is 100.
S1 And what's on the y-axis?
S2 Number of molecules. I don't know if I'm actually doing this to scale or anything. <u>Okay so here's 30 degrees right. The water is really cold, but still there's a very small portion of molecules throughout here forming that are in vapor. They're in gaseous condition.</u>
<u>Ln 660. S1 But there's a lot before too, right?</u>
<u>S2 What do you mean there's a lot before?</u>
<u>S1 Isn't there vapor pressure up here too if it's a liquid?</u>
<u>S2 Well no. I think anything before this is point on the graph.</u>
S1 That's the only thing I'm arguing, I understand everything else. (laugh)
S2 Yeah well okay, I mean it's like this portion of the graph is this okay, and then anything past that portion.
S1 <u>No, but there'll always be vapor pressure there if it's a liquid. It doesn't just start when it gets to boiling.</u>
S2 <u>Well I feel as though at 0 degrees Kelvin there will be absolutely no vapor pressure</u>, no molecules or what so ever, but yeah? *(In-depth pair session 3)*

Extreme case →

<u>**Classroom observation notes and in-depth pair session portions not coded.**</u> Close to 100% of the classroom events could be coded using these codes and sub-codes. Events that were not coded in the classroom observations were classroom administration of details regarding assignment deadlines. Events that were not coded in the in-depth pair sessions were the technical difficulties or casual conversation. For

example, the following interactions were not included in the analysis of the in-depth pair sessions:

> Ln 230. S2 Uh oh. That's not good.
> T It's just locked up.
> S2 Okay.
> T Wow how bad is that. Ha.
> S2 Yeah I hate when that happens. (computer problems)
> *(In-depth pair session 1)*.
>
> Ln 42. T I need to warn you sometimes because my computer's not really set up for the dual mouse thing; sometimes the computer will lock up. *(In-depth pair session 3)*.
>
> Ln 5. T What we're recording now to set specific record time, push record key. SLP, super long play. Is that okay?
> I I think I could go even higher. Like you can leave it up.
> T All right then I don't know how to do it so.
> I Okay well that's fine.
> T It is what it is (laugh).
> I Yeah.
> T One thing we should do let's just make sure the (garbled) is recording.
> I Yeah. *(In-depth pair session 4)*.

3.8 Checks

Checks for internal and external consistency were conducted during the coding of the classroom observations and the transcripts of the in-depth pair sessions. These checks included :

1. Internal checks for similar coding across the classroom observation notes within and among classes and within and among the 6 in-depth pair session transcripts.
2. Blind re-coding of portions of the transcript of the in-depth pair session 1 and 2.
3. External peer review of codes and submission of coded transcripts to national conferences.
4. External checks of codes against definitions.

Thus, the application of the codes to the transcripts of the in-depth pair sessions was considered to be consistent.

3.9 Code analysis of the in-depth pair sessions

The coded in-depth pair sessions were examined for evidence of student engagement with complex processes. Where possible, the data from the in-depth pair sessions were triangulated with the CAT survey data from the classrooms.

CHAPTER 4

FINDINGS

4.1 Introduction

An initial test of scientific inquiry skills revealed that students enrolled in a introductory chemistry class produced the most significant gains after class instruction compared with other introductory chemistry courses at the same institution. While there may be a number of environmental factors that could have contributed to the gains in the initial test scores, students in this class were surveyed at the time (n=56) , and out of 9 factors, ranked class discussion with the teacher and peer discussion around the computer as the most important contributors to their learning (Khan, 2001). The purpose of this case study was to analyze the instructional strategy in this introductory chemistry class to understand how it may have contributed to the gains in inquiry skills that emerged on the initial test (1.4.1). Classroom observations of the introductory chemistry class were conducted in order to analyze the instructional strategies in this class. This class is referred to as the "primary case."

In addition to observations of the primary case, two other introductory chemistry classes were also observed (Lecture 1, Lecture 2). These two classes of introductory chemistry were at the same institution as the primary case. Although all three classes covered the same syllabus and were offered at the same institution, they were different in many other aspects—including approaches to instruction. The next sections in this chapter report the classroom environments of each class, the approaches to instruction that were observed within each class, and the classroom interactions within each class. The reports were based on data collected from classroom observation notes and documents, classroom observation rubrics, and CAT student survey items about the classroom environment. approaches to instruction, and classroom interactions.

4.2 Introductory chemistry classes

The classroom environment of the three classes was similar in two respects: the department wide introductory chemistry syllabus and the OWL homework assignments were the same among all three classes. The classroom environment of the three classes were different in a number of respects, three of which are the physical setting, teachers, and the students.

Table 15. Classroom environments.

	Primary case	Lecture 1	Lecture 2
Physical setting	Small computerized classroom with 26 terminals	Large lecture theater with demonstration table and computer station	Large lecture theater with demonstration table and computer station
Teachers	Primary case teacher New faculty member	Lecture 1 instructor	Lecture 2 instructor
Students Se 15, 2000	33 students total (9 honors)	125 students total (13 honors)	122 students total (14 honors)
Class Syllabus	Department wide introductory chemistry syllabus incl. an additional 2 lessons on organic chemistry	Department wide introductory chemistry syllabus	Department wide introductory chemistry syllabus
OWL resource /homework	21 + 0 optional	21 + 4 optional	21 + 1 optional

The classroom environments had the same department wide introductory chemistry syllabus syllabus and OWL homework but different physical settings, teachers, and students. The physical setting, the students, and the teachers will be described here.

<u>**The setting.**</u> The primary case took place in a classroom with 26 computer terminals. Each terminal also had a stand up microphone. Pairs of students were seated at each

terminal. The terminals were positioned in concentric curves that were all facing towards the front of the classroom. In order to see the front, each successive curved row was higher than the next. The instructor had his own computer terminal at the front and off to the side of the room. An overhead enabled a projection of his computer screen and individual students' computer screens for the whole class to see.

On the other hand, the Lecture 1 and 2 classes took place in a large lecture theater that had one demonstration table and a computer station for the instructor. The instructor could project the computer screen for the students to see.

4.3 The students

4.3.1 Student registration for introductory chemistry

Many science and applied science degrees required a first class in chemistry, leading to large enrollment in these introductory courses. The students who enrolled in introductory chemistry came from a wide variety of science and applied science backgrounds, such as biochemistry, engineering, environmental science, food science, biology, exercise science, plant and soil science, and nursing. In addition, some non-science majors, such as psychology or education students could have elected to take an introductory chemistry class to fulfill a general science requirement.

The primary case was a requirement for all chemistry majors, although many other students had access to the class via telephone registration. The students who had access to the class via telephone registration included any honors student with any major[8], honors chemistry students, non honors chemistry majors, and non honors, non chemistry majors such as engineering and biochemistry students. Students who did not

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[8] Honors students were part of a community of close to 2000 first year students at the university with an average high school rank in the top 8 percent. Honors students had a variety of academic majors.

carry these majors were blocked from registering for this class over the phone and had to obtain special permission to take the class from the department. According to the department, these requests were rare.

The lecture classes, however, were accessible to all students via telephone registration regardless of their major or honors or non-honors designation. The students in these courses included honors and non-honors biology, nursing, communications, education, and arts students. Both the primary case and the lecture classes had waiting lists for their class.

Table 16. Student registration.

	Primary case	Lecture 1	Lecture 2
Total number of students Se 15	33	126	122
Majors	Chemistry, science, applied science, biochem., other	Not chemistry, science, applied science, other	Not chemistry, science, applied science, other
Number of honors students & their majors	9 (chemistry and not chemistry majors)	13 (not chemistry majors)	14 (not chemistry majors)
Prior high school courses	One to two courses in chem	0-2 courses in chem.	0-2 courses in chem

According to Table 16., there were less students enrolled in the primary case compared with the lecture classes, and there was a higher proportion of honors students to non-honors students in the primary case than the lecture classes.

4.3.2 CAT pre- survey results

Pre and post CAT surveys were administered to the students from all chemistry classes. The surveys were designed to gauge students' perceptions of their learning experiences in the class and in previous science classes. The survey was administered on-line before and after instruction in the three chemistry courses. When students entered introductory chemistry courses, there were no significant differences (t test, p>0.05) between the primary case (n=33) and the lecture classes (n=126 , n= 122) in the following CAT pre-survey items:

1. I believe that student participation in the class will contribute to my understanding of chemistry.
2. I was frequently asked to analyze data from a graph or table in previous science courses.
3. I am not comfortable developing hypotheses in chemistry.
4. I am able to design an experiment to determine a relationship between two variables in chemistry.
5. I have experienced opportunities to generate scientific ideas in previous science courses.
6. I have been asked to challenge or evaluate scientific ideas in previous science courses that I have taken.
7. I understand how scientists assess and modify theories about unobservable processes.
8. Qualitative rules or concepts that are descriptive and non-mathematical help me understand chemistry.
9. I have been asked to generate conclusions about scientific data that is from a computer simulation.
10. Peer discussion is valuable for my understanding of science topics.
11. High school chemistry laboratories were good representations of how scientists generally solve chemistry problems.
12. When something in science does not behave according to my expectations, I persist until I understand the rules.

Thus, it appeared from these CAT pre- survey responses that students from all three classes had similar perceptions about their prior experiences in science and similar beliefs about the factors that could enhance their learning. In addition, students from all three classes reported similar abilities in being able to design experiments and understand how scientists assess their theories, according to their CAT pre-survey responses.

There were significant differences (t test, $p<0.05$), however, between the primary case students and both lecture classes' students in interest in chemistry on the CAT pre-survey. There was a significant difference between these groups on other CAT pre-survey items as well (n=33, n=126 and n=122):

1. Chemistry is one of the more interesting sciences ($p< 0.05$ agree with this item in the primary case compared with lecture classes).
2. I am not anxious about using computers in science ($p< 0.05$ agree with this item in the primary case compared to lecture 1 only).
3. I am confident about my ability to solve chemistry problems ($p< 0.05$ agree with this item in the primary case compared to lecture 1 only).
4. Reading and reviewing problems in a textbook is usually where I learn how to solve problems in chemistry ($p<0.05$ disagree with this item in the primary case compared with lecture classes).
5. It is important for me to understand where the concepts come from in chemistry ($p<0.05$ agree with this item in the primary case compared with lecture classes).
6. There are few opportunities for students to make and test their own predictions in science courses ($p< 0.05$ agree with this item in the primary case compared to lecture 1 only).

According to the pre and post CAT surveys, these differences between student responses from the primary case and student responses from the lecture classes remained significant both at the beginning and end of the semester of chemistry instruction.

Within each of the three individual classes, however, there were no significant differences on the CAT pre-survey between honors and non-honors students within every class on their survey responses to items on interest in chemistry, persistence anxiety about computer use, confidence, abilities and perceptions of prior science instruction. There was one significant difference that emerged between honors and non-honors students in Lecture 1 on one item only (I am confident about my ability to solve chemistry problems, Lecture 1: n= 11 honors students, 115 non-honors students, $\chi 2$ p <0.05), but this could have been due to a Type 1 error. Thus, according to the CAT pre-survey, students entering any of these three classes reported similar prior experiences in science and perceptions of their abilities, regardless of whether they were honors or non-honors students or in the primary case or in the lecture class. There were, however, significant differences between the student body entering the primary case and the student body entering the lecture classes on several CAT pre-survey items. Students entering the primary case were more interested in chemistry, more confident about their abilities to solve chemistry problems, and less anxious about using computers in science than their peers in the lecture classes, according to the CAT pre-survey.

4.4 Classroom resources

Introductory chemistry classes primarily used two resources to supplement classroom lessons. The resources were technology and a textbook. There were three potential places where technology was integrated into the introductory chemistry class: Chemland, OWL, and classroom web sites. All three instructors chose to use Chemland, OWL, and web posting to varying degrees in their particular class.

4.4.1 Access to Chemland

The primary case took place in a classroom with 26 computer terminals. Every computer was equipped with the software Chemland 6.0. Chemland 6.0 was a suite of freely available exploratory general chemistry educational computer programs that were produced to augment lectures for introductory level chemistry with discovery based learning exercises. Many of the computer programs contained animations and simulations of lab results. The simulations were available to all chemistry instructors via the Chemland 6.0 website, but each instructor chose to use them to different degrees in their classrooms.

Table 17. Use of Chemland in class.

Class	Use
Primary case	Every class
Lecture 1	Not at all
Lecture 2	On occasion, on a demonstration computer

All introductory chemistry students, regardless of how often Chemland was used in the class, could access these interactive computer tools at home in three ways. Chemland Chemistry Software was readily available on the Internet and was included with the required textbook for all introductory chemistry students "Chemistry and Chemical Reactivity", Kotz and Treichel, 4th ed. All students also had access to Chemland via the Chemistry Resource Center (CRC). Thirdly, some of the Chemland interactive tools were a part of the OWL modules. In these three instances, however, students did not have teacher guidance while using the Chemland interactive tools as they would if the interactive tools was introduced in class.

4.4.2 On-line homework system (OWL)

All three classes required students to use an on-line, web based learning (OWL) system for their homework assignments. All students were notified that they needed an internet account and that computers were also available to them at the CRC or multiple sites on campus. OWL was a comprehensive homework system that included the delivery and grading of electronic homework assignments, an authoring tool for instructors to construct homework questions, student rosters and graded reports. Students logged into OWL through their web browser and then proceeded to answer assigned homework questions in a specific module. When students submitted a response to a homework question, OWL automatically graded their response and displayed the correct answer along with instructive feedback written by the instructor. OWL presented students with questions on a particular topic until a certain number were correct before students moved onto the next topic. Scores were stored in a database so that both students and their instructor could track their progress. Students were able to repeat assignments as desired to try and better their grade. The following topics were programmed in OWL: Lewis Structure Tutor, Nomenclature, Net Ionic Equations, Oxidation-Reduction: Intro, Thermo: First Law Thermo: Specific Heat Capacity,Thermo: Calorimetry, Thermo: Enthalpy of Reaction, Thermo: Bond Energy Calcs, Electromagnetic Radiation, Electronic Structure, Periodic Trends, Molecular Geometry Tutor, Molecular Structure, Gases, Titrations, Stoichiometry, Orbital Energy, Electronic Configuration, Polarity, Boltzmann Distribution, Crystal Structures, and Electromagnetic Spectrum.

The lecture instructors assigned 22 modules for homework and the primary case teacher assigned 23 modules for homework. The Lecture 1 instructor recommended an additional 4 optional modules and the Lecture 2 instructor recommended an additional 1 optional module.

Table 18. Different topics assigned for homework in OWL.

Chemland module	Primary case	Lecture 1	Lecture 2
Net ionic equations	No	Yes	Yes
Redox intro	No	Yes	Yes
Titration	Yes	No	No
Balancing	No	Yes	Yes
Ionic compounds	No	Yes	Yes
Specific heat capacity	Yes	No	No
Calorimetry	Yes	No	No
Atomic absorption	No	Yes	Yes
Polarity	No	Yes	Yes
Gas laws	Yes	No	No
Boltzmann distribution	Yes	No	No
Electromagnetic spectrum	Yes	Yes	No
Electromagnetic radiation	Yes	Yes	No
Balancing	Yes	Yes	No
Orbital energy	Yes	Yes	No
Bond energies	Yes	Yes	No
Enthalpy	Yes	Yes	No
significant figures	No	No	Yes

Thus, according to Table 18., for the most part, the OWL homework assignments in all three classes were the same.

4.4.3 Class websites

Another resource available to all introductory chemistry students was a class web site. Every class in introductory chemistry had their own web site. The web site contained information about where to contact instructors, the class syllabi, old exams, lab schedules, pre-lab quizzes, lab procedures, and in some cases, videos of lab procedures.

4.4.4 Syllabus and textbook

The syllabus for all three classes was the same department wide introductory chemistry syllabus. Each topic in the syllabus was associated with a chapter from a text. The text was considered to be a reference for class material. All students in all three classes used the same textbook, "Chemistry and Chemical Reactivity", Kotz and Treichel, 4th ed. Assigned textbook chapters were the same for both lecture classes except the primary case also covered Ch.11, a chapter on organic chemistry and advanced molecular structure.

4. 5 The teachers

The primary case teacher was the department head of introductory chemistry at the university institution where the study took place. His colleagues, the Lecture 1 instructor and Lecture 2 instructor agreed to also participate in the study. All the teachers received similar ratings on teacher effectiveness in previous years' departmental surveys (personal communication). A second teacher in the primary case was new faculty this year and did not have a departmental survey rating her effectiveness yet. She was co-teaching with the primary case teacher on occasion. Although the new faculty member had previous teaching experience in chemistry, she attempted to follow the primary case teacher's approach to teaching the primary case. All four teachers in this study reported they had similar content and process goals for the introductory chemistry class.

4.6 Summary of the classroom environments

The classroom environments of three introductory chemistry classes shared some similarities, but also had some important differences. The primary case and the lecture classes shared a common department-wide syllabus and common classroom resources such as the text, the CRC, and the OWL homework system. According to the CAT pre-survey given to students enrolled in the primary case and the lecture classes at the beginning of their semester, the students from all three classes reported similar prior experiences in science, and perceptions of their persistence and abilities at the beginning of the semester. In addition, all of the teachers shared similar content and process goals for their students.

The primary case and the lecture classes, however, were different in a number of important respects: they had different classroom settings and sizes, differences in student interest in chemistry and anxiety towards computers as reported in the CAT pre- survey, and different teachers. The primary case was in an electronic classroom with 33 students registered for the introductory chemistry. The electronic classroom housed 26 computer terminals that were equipped with Chemland software. The lecture classes, on the other hand, were in a large lecture theater with over 120 students registered for introductory chemistry. Compared to the lecture classes, the students in the primary case also had a higher proportion of honors majors than students enrolled in the lecture classes, and more students in the primary case reported being interested in chemistry and confident about their problem solving ability (significant difference only between the primary case and lecture 1 on this survey item) in the CAT pre-survey than students enrolled in the lecture classes. Because of these differences between the primary case and the lecture classes, lectures 1 and 2 were not designated as controls for this study. The focus of this study, rather, was not on these differences between the cases, but the primary case itself, and in particular, the instructional strategies in this primary case. Thus, any comparisons made were chiefly contrasting instructional strategies between the primary case and lectures 1 and 2. These comparisons were made not as a controlled experiment, but as an attempt to acquire initial data on the question of whether the primary case teacher's instructional methods departed in some way from the normal teaching methods within this chemistry department.

4.7 Instructional strategies

4.7.1 Pattern of instruction in the primary case

While there were a number of factors that could have contributed to students' progress in the primary case, the purpose of this section was to explore one of those possible contributing factors: the approach to classroom instruction in the primary case. Classroom observations of the primary case were conducted in order to uncover the central pattern of instruction in this class. Twenty sets of classroom observation notes of the primary case in total were collected over 3 semesters (16 from Fall 2000) and analyzed using a constant comparative approach (Glaser & Strauss, 1967). In addition, 10 classroom observation rubrics and 33 pre and post CAT surveys were administered to students from the primary case and analyzed using an SPSS statistical package. A pattern of instruction emerged from the analysis of the classroom observation notes that was documented and reported in the context of observations of other methods of instruction in the introductory chemistry department, as represented by lectures 1 and 2.

Primary case teacher goals. In a faculty interview, the teacher of the primary case described his goals for the class: "I want them to learn chemistry, [but] I don't want them to just understand the concepts--I want them to understand where to get the concepts and where they come from" (Khan, 2001). To accomplish this, the primary case teacher described his approach to instruction as "...lead[ing] them through the use of the simulations in a fashion that lets them look at individual pieces of relationships at a time, and then lead[ing] them through putting [those pieces of relationships] together into an overall concept... And that's where the simulations come into play--students use the data from the simulations to try and figure out relationships."

Primary case typical lessons. A consistent pattern of instruction emerged from the analysis of 20 lessons from 3 semesters of the primary case (Fall 1999, Spring 2000, Fall 2000). Two typical lessons are presented below in Tables 19 and 20. The first lesson in Table 19 was from the topic of bond angles and the second lesson in Table 20 was from the topic of vapor pressures and boiling points. A general description of the teacher's activity is suggested in the first column of the tables and the transcript of the lesson is in the second column of the tables.

Table 19. A lesson on bond angles in the primary case.

Teacher activity	Transcript of lesson on bond angles
Teacher provided background information	1115H T I want to take up bond angles and look at their shapes and properties so that we can predict their behavior.
Teacher asked students to compile information using the computer tools	T Try to collect bond angle data on ethane using the computer animations. One side of the class also do methanol and formaldehyde and the other side do boron trifluoride and ozone. 1123H Data is gathered from students and recorded as bond angles on an overhead which has pictures of the molecules.
Teacher asked students to **generate** relationships	1130H T Take these numbers (referring to bond angles that were gathered), and relate them to the Lewis Dot structures of these molecules and come up with rules for predicting structures. What kind of bond angles do they fall in? (Teacher starts writing on the board) 8 electrons or less on the central atom.

Teacher activity	Transcript of lesson on bond angles
	S provide the numbers 109, 120, and 180 and they are recorded on the board. T Now come up with a set of rules for how you can go from a Lewis Dot structure to a bond angle. S discuss in groups for 5 minutes. T writes on the board: triple bond; double bond; single bond. S provide the bond angles by each one (bond angles of 180, 120, 109, respectively are provided. This is the generalization).
Teacher asked students to **evaluate** relationship in light of new information.	1147H T What works for this? (Uses an overhead with pictures of additional molecules and points out those with triple, double, and single bonds). T Which have those bond angles stated in the above generalization? S1 But BF_3 doesn't follow the rule and neither does NH_3!
Teacher guided **modification** of relationship	T Why do you think that is? S1 BF_3 has less electrons on the central atom so may be that's why it's not 120. S2 Why isn't there a double bond in BF_3? T BF_3 is a borderline case. It's just that fluoride holds onto its electrons extremely well--more than others.
	1150H S3 So if there's 2 lone pairs on the atom, the bond angle's 180 and if there's 3 lone pairs on the atom then the bond angle must be 120. S4 I have the same thing! T records modified rule on the board S If there's 4 lone pairs, the bond angle is 109.
Teacher asked students to re-evaluate modified rule.	1155H T Let's find anything that violates that rule (referring to modified rule on board).

Based on the transcript of the first lesson documented in Table 19, one sees the following sequence: the teacher provided background information; the teacher asked students to compile information using the interactive computer tools; the teacher asked students to generate relationships; the teacher asked students to evaluate the relationship in light of new information; the teacher guided the modification of the relationship, and the teacher asked students to re-evaluate and modify the rule. In the second lesson on a different topic in chemistry: vapor pressure and boiling points, a similar pattern of teacher activities emerged.

Table 20. A lesson on boiling points in the primary case.

Teacher activity	**Transcript of lesson**
Teacher provided background information	T These curves [referring to a graph in the vapor pressure simulation] are actually used for identifying boiling points. What we really think of as boiling points and the boiling point is defined as the temperature at which this curve reaches 760. 760 is atmospheric pressure, so when the vapor pressure reaches atmospheric pressure, that's when things boil.
Teacher showed students how to compile information about boiling points from the interactive computer tools	T So let's go ahead and just look at what the boiling points are for these things. What we do is we just kind of back off down this curve until we reach 760. So for ethanol it's somewhere between 70 and 80 degrees. So ethanol's between 78 and 79 degrees. It's boiling point. So methanol is between 64 and 65 degrees. S2 Uh, huh.
Teacher asked students to **generate** a relationship	T Does that make sense? So what do you think the relationship between molecular weight and boiling point is? Come up with just something like that. What's the relationship between boiling point and molecular weight? S1 [pointing to a graph in the vapor pressure simulation] As the molecular weight increases, the boiling point also increases because for ethanol it's more, it has a greater molecular weight and the temperature it takes for it to boil is between, did he say 70 and 80? S2 Uh, huh. Something like that. Well we can check.

Teacher activity	Transcript of lesson
	T What are you doing? S1 S2 No we're just checking. T Oh, okay. I'm sorry. S2 Yeah between 78 and 80 [referring to a graph in the vapor pressure simulation] and so. S1 As molecular weight increases the boiling point increases. S2 That's right. S1 The boiling point is greater. S2 The boiling point is, yeah she's right. T So as molecular weight goes up, vapor pressure goes down and therefore boiling point goes up.

Teacher activity	Transcript of lesson
	T Okay so the next thing we then want to do is look at that trend that you said that the boiling point should go up as much as the weight goes up. We're going to do that, the thing that just looks at boiling points. And before we do this I need to give you a hand out. Molecules are often thought of as a carbon group and something else stuck to it and the carbon group is often called an alkyl group and so here's a number of alkyl groups and some of these alkyl, these are like the straight alkyl group, some of them are the same weight but different shape like the carbon's branch. So what we want to do is we want to start out, we want to use this to see if your trend there actually works for more than say two compounds. So the first thing to do would be to keep this as hydrogen and look at the relationship between molecular weight. This will make a graph for you of the boiling point and molecular weight, then you vary how large this alkyl group is. How big the molecule is and it shows you a picture of the molecule as you go along.
Teacher asks students to **evaluate/modify** relationship in light of new information	So go ahead and do that. You can hold onto this and see if it seems to, if your rule seems to hold. S2 (click) So as we go down here the boiling point does increase. (click) T Some of them don't move because they're the same number of parts, so they have the same weight. So decide whether it not it works. S2 Yeah it works. S1 It does work. S2 It works because as you come down in the weight, as the weight increases the boiling point also increases. T Okay. So that seems to confirm what your are saying in terms of molecular weight and boiling point.

Teacher activity	Transcript of lesson
Teacher asked students to evaluate/modify relationship in light of new information	T Okay, so now what else could we do? What else should we study? S1 We could do another functional group to just to be sure, but we. S2 I don't think it would change anything. T Oh it's worth a try. Go ahead and do it. S2 Exactly the same. S1 Exactly the same. T Oh, so just thinking back to what you had for chlorine how does that look different than the chlorine one? S1 It actually seems like they're moving over. T Okay. S1 On the graph because they're getting heavier and heavier to begin with because the functional groups are getting heavier and heavier as you move down. T Okay so what other study could you then do? S1 Umm. T So that's the chlorine line and the other one over there is the iodine line. S1 Uh, huh. S2 Yup. S1 We could try it without a functional group at all and you'd have to have one. T That's a good idea and actually that's the way people think about it. That's what hydrogen is, hydrogen is actually not a real functional group. S1 Oh, okay. T Well what about leaving one alkyl group and changing the function groups and see what happens then? See if it works when you just change alkyl groups. Actually why don't you choose a longer one? S2 Oh, okay. S1 Reset that? T Yeah. S1 Okay. (click) S2 Why does this thing appear? S1 Do you need that? Hydroxyl. S2 Hydroxyl. S1 The OH. S1 The hydroxyl, well we'll see that. S2 It's the only one that's not in.

Teacher activity	Transcript of lesson
	S1 In the line. It's not linear. It's sort of higher. S2 Yeah, it's. S2 It stands out. For some reason. S1 It doesn't follow the trend. S2 It doesn't follow the trend.
Teacher asked students to evaluate/ modify relationship in light of new information	T What should you check? S2 It's weight. T That's accurately portrayed on here, so it boils at normally high or low for it's weight. S1 At high. S2 Yeah. S1 It boils high for its weight because chlorine boils lower and that's much, that's heavier. T Okay so the way to confirm that something that has to do with the OH? S1 We could try another alkyl group. See if it follows the same trends. S2 Yeah we could. S1 So I guess let's try something light like ethyl. S2 Yup. S1 Uh, huh. S2 Yeah it does. S1 It still does the same thing. S2 Yeah. S2 The hydroxyl still boils at a higher rate it doesn't follow the same trend as the other. S1 These others increase almost linearly. Almost in a line, but hydroxyl's kind of out at it's own boiling point. S2 Hydroxyl's right here and it's. S1 Right it's far away. S2 Abnormally high. S1 It's abnormally high because chlorine which is heavier than hydroxyl, it boils at a lower boiling point that hydroxyl does. T So let me ask this a different way. I think that might have been too open-ended. So right there you're saying boiling point depends on molecular weight and nothing to do with what the molecule is, just how heavy it is. For lots and lots of things that seems to work, but now it looks like there were things that have the same

Teacher activity	Transcript of lesson
Teacher guided modification of relationship	molecular weights, but have very different boiling points. So boiling point depends on what then? S2 Do you mind if I draw or? T No you can draw there. S2 Okay. Wouldn't the, on this one say, remember how we were talking about how there would have to be a bond between things in a liquid to hold them together as a liquid. S1 Uh, huh. S2 What do you think about the bond, what kind of bond there would be between two hydroxyls? S1 Two hydroxyls? S2 Would it be a stronger bond than say between two chlorides or two bromides? S1 Most likely because between two hydroxyl groups? Between and OH and an OH? S2 Like between an OH and an OH. S1 Well you could always. T So they stick together a lot and therefore the bonds between the molecules are called the intermolecular forces. They are unusually strong that the OH groups and because of that they tend to have higher boiling points. And do you think they have a higher vapor pressure or lower vapor pressure? S1 Lower vapor pressure.
Teacher asked students to re-evaluate modified rule	T Okay, so the next thing we want to do then is we want to go back and check. Do a test of that modification to your rule and so we're going to go back to the vapor pressure molecule we looked at before. And what we want to do is we want to look at two compounds. One we want to look at is water and the other one we want to look at is called benzene. So we're not going to do that yet, but I want to show you that. So water. You know what water looks like. Water has a molecular weight of 18. This is benzene so it's a flat ring and so it doesn't need OH's or anything like that. It has a molecular weight of 78. So for your original rule of just molecular weight, which of these would have a higher vapor pressure?

Teacher activity	Transcript of lesson
	T Water or. S1, S2 Benzene.

<u>The pattern of instruction in the primary case.</u> These two lessons that were transcribed in Tables 19 and 20 were typical of the primary case teacher's approach to classroom instruction in the 10 primary case lessons that were observed. Although the two lessons were about different topics (bond angles and vapor pressures), a central pattern of teacher activities appeared to emerge in the primary case. The primary case teacher typically began every class by introducing the target concepts and skills or revisiting prior concepts covered in previous lessons. The primary case teacher showed students the variables and modeled how to manipulate them in the interactive computer tool. The primary case teacher then challenged pairs of students to compile information from the interactive computer tool or showed them how to do it, and asked student pairs to generate a relationship that accounted for patterns in the information. After generating a relationship, the class was then asked by the primary case teacher to gather additional information from the interactive computer tool or other sources in order to evaluate the scope of the relationship. Sometimes, the primary case teacher would ask students to "find information that confirms the rule" or to "find information that violates the rule". Vigorous group discussion ensued between student pairs when anomalous information was found and tested against the relationship. At this point, with teacher guidance as a whole class or in small groups, students were observed modifying their hypothesis in light of the new evidence in the primary case. The primary case teacher asked students to explain their thinking and encouraged students to re-enter this cycle of generating relationships, evaluating relationships to explain discrepant information, and modifying the initial relationship. Generating and cycles of evaluating and modifying relationships in chemistry were referred to as GEM cycles. The entire instructional strategy, referred to as the "guided discovery approach" with interactive computer tools cycles. The entire instructional strategy, referred to as the “guided discovery approach” with interactive computer tools or simply, the GD approach to instruction, contained teacher activities to trigger iterations of GEM cycles as suggested in Figure 3.

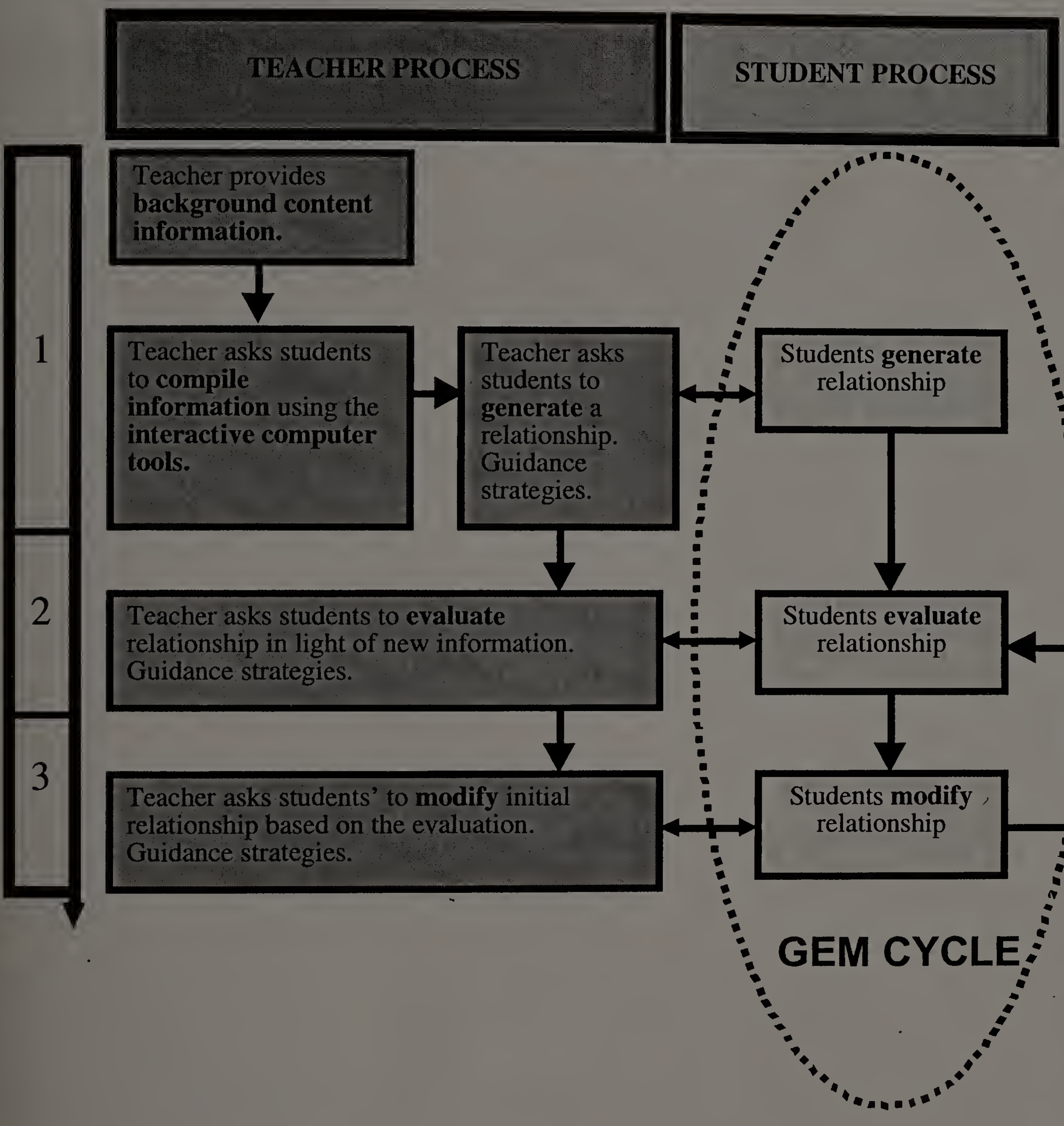


Figure 3. The guided discovery approach to instruction.

4.7.2 Pattern of instruction sustained in the primary case

Although the two lessons in the primary case were about different topics (bond angles and boiling points), a similar approach to instruction was employed in every class that was observed despite the topic in introductory chemistry. The GD approach was observed, on average, 2 times per classroom period (minimum once, maximum, 4 times); thus, GEM cycles were observed, on average, twice per classroom period. This finding means that over 52 GEM cycles in total occurred throughout the semester. This classroom observation was further supported by post CAT survey data from students surveyed in the primary case class at the end of a semester of instruction (n=22):

1. Fully 100% of primary case students agreed that, "There are more frequent opportunities to generate scientific ideas in this class than most other classes."
2. 81% of surveyed students agreed that, "I am asked to challenge or evaluate a scientific idea more often in this class than my other classes."
3. 95% of surveyed students agreed that, "I have been asked to construct explanations about scientific information that was presented in a computer simulation."

Thus, a pattern of instruction appeared to emerge from analysis of classroom observations notes in the primary case. This pattern of instruction was termed "the guided discovery approach" with interactive computer tools or the "GD approach" to instruction. The GD approach to instruction contained teacher activities that appeared to trigger generating relationships between two variables and cycles of evaluating and modifying relationships (GEM cycles) in chemistry. Furthermore, the GD approach to instruction was sustained despite the different topics in the syllabus, with over 52 GEM cycles occurring throughout one semester of introductory chemistry instruction.

4.8 Specific guidance strategies

The GD approach to instruction contained teacher activities in the primary case that appeared to trigger the generation of relationships between two variables and cycles of evaluation and modification of relationships (GEM cycles) in chemistry. But it was also observed that these main teacher activities in the primary case appeared to be coupled with key specific guidance strategies.

According to the primary case teacher, it was the specific guidance strategies that made the class run well or not. How the primary case teacher used specific guidance strategies is articulated from a faculty interview with the primary case teacher.

> One of the things that makes a class like this run well or not well has to do with the feeding out of hints for exploring. That is, you don't just give the students a whole bunch of stuff and ask them to come to a conclusion. You have to give them guidance along the way as to what to look at. So if there's something like looking at trends in the periodic table, you don't just say, 'Here's the periodic table. Here's a bunch of data for it. Do you know what controls the atom size or what controls this or that?' You have to kind of say, 'okay let's look at this little subset first. What do you see? Why do you think might happen? Now look at this other subset. What happens here? Is it the same? Is it different? Why do you think it's the same or different?'
>
> You have to feed it out piece by piece along the way. And that is probably the thing that makes it either work or not work best. Well one of two things: the feeding out of the information piece by piece so that they do things in an order that will make sense to them. That's one thing. The other thing is you need to ask the questions, when you ask them to explore things, you need to ask the questions in a particular way. If you ask them just factual questions, they can just answer them and very often they won't actually think about it. So if you just ask them what's the radius of this, they will just look it up, and it's a data point. It's a data thing. It's not a relationship or conceptual thing. So what you have to do is, you have to say, 'Look at this grouping, and what do you think happens there, or why do you think this happens?' You have to ask questions in a way that's open-ended-- that they actually have to think about it and discuss it, as opposed to, it's a simple yes or no answer.

Thus, the primary case teacher appeared to ask thoughtful questions bit by bit. These specific forms of guidance were considered by him to be a key instructional component of the GD approach.

From classroom observation notes, the GD approach to instruction appeared to contain teacher activities that triggered GEM cycles and were associated with specific guidance strategies. Furthermore, the GD approach to instruction appeared to be fully integrated with interactive computer tools. The focus of this section is to identify and describe the specific guidance strategies and the integration of interactive computer tools, with examples from classroom observations of the primary case.

As an advanced organizer, Table 21, below lists the specific guidance strategies and instructional uses of the computer that were associated with teacher activities in the primary case.

Table 21. Table of teacher activity structures, guidance strategies, and computer affordances in the GD approach to instruction.

Phases of the guided discovery (GD) approach	**Major strategy supporting GD and GEM**	**Teacher guidance strategies**	**Teacher affordances with Chemland**
Background information	Provided content information	Analogy	
Compile information	Asked students to compile information from a source Identified the variables	Demonstrated Chemland software Selected the variables, cases, data points in Chemland software Displayed the output graph in Chemland software	Teacher constrained initial variables
Generate Relationship	Asked students to find the trends!	The extreme case Incremental values Comparisons Why?	Teacher encouraged students to generate a large amount of information quickly Teacher asked students to compare color coded curves on the graph or color coded animations

Phases of the guided discovery (GD) approach	**Major strategy supporting GD and GEM**	**Teacher guidance strategies**	**Teacher affordances with Chemland**
			Teacher asked students to push variables to extreme temperatures/ concentrations/ conditions Teacher encouraged students to dynamically generate graphs and multiple representations as output Teacher encouraged students to move variables in step by step increments
Evaluate/Modify the relationship	Provided discrepant information	What's wrong with this? Why doesn't this make sense? Predict! Compare! Work back from the data! See if it holds true Design a new test The comparison Why?	Teacher asked students to compare color coded curves on the graph or color coded animations Teacher encouraged students to gather information quickly Teacher asked students to rerun the graphs
	Provided an extreme case	Consider new variables, new data points Why? Make comparison	Teacher encouraged students to select different variables, controlled for others in order to design new tests
	Provided a confirmatory case	Make comparisons! Predict! Why? Find more information	Teacher encouraged students to view the animations at the molecular level Teacher encouraged students to move variables in increments and steps

The section below includes the teacher activities within each phase of the GD approach to instruction. Associated with these teacher activities were specific guidance strategies. These guidance strategies will be the focus of this section. The specific guidance strategies will be described in detail with examples of the guidance strategy from the primary case.

4.8.1 Background information phase

The primary case teacher began the guided discovery (GD) approach by providing background information on the topic. It was during this activity, that the primary case teacher was also observed suggesting an analogy. Suggesting an analogy was a guidance strategy that was observed when the primary case teacher was providing background information. Examples of analogies from the primary case are documented below:

Analogies. Analogies were defined as evidence of instructor actions to promote or suggest an analogy or metaphor (key words: like, as if). This guidance strategy appeared to be designed to facilitate understanding about the nature of scientific investigation (Lesson 1), or abstract concepts (Lesson 7) or processes (Lesson 10) in chemistry. The analogies are underlined in the following examples from classroom observations of the primary case on the next page.

For example:

> Eg. Lesson 7.
> S8 Do resonance structures co-exist all the time?
> It is a mixture of the two all the time.
> S9 Doesn't mean it's one or the other?
> <u>T Right, it's like a mixture of colors like purple.</u>

> Eg. Lesson 10.
> T referring to Boltzmann distribution for oxygen and range of speeds as represented under a curve. They [the oxygen molecules] go at a range of speed, so some are going slow, some are going fast. <u>And so it's very much like a plot of cars on a highway.</u> So some cars are going like 90, very few of them are going 90, lots of them are going you know a bunch are going 80, most are going you know 60 or 70, very few are going 30 or 40 or whatever. So it's like if you were watching a highway for a long time. So that's what this is for gas molecules.

During the background information phase of the GD approach, the primary case teacher was observed providing content information. Content information was observed in several instances to be enhanced with an analogy. In these cases, analogies were considered to be guidance strategies because they were used to support the main teacher activity. Thus, we observed analogies coupled with providing content information during the background information phase of the GD approach.

4.8.2 Triggering GEM cycles

The primary case teacher described when to start triggering GEM cycles.

> [T]he time to be able to do it [begin GEM cycles with the computer simulations] is [when students] know what it is they're looking at. They need to know what the information is telling them in each data point by data point instance, but the thing that they should not know before they start looking at it is what the overall relationship and guiding principles are.
>
> So...for instance, say you are looking at ...ionization energy for elements. There's lots of really good ways to teach trends in that. And there's a lot of understanding about how electronic structure and atoms work because of it, but you would not use the simulation to get them to know what ionization energy is.
>
> So what you would do is you need to tell them ionization energy is the following thing. And that's just something, they don't discover that, you

> just tell them that, so they know what it is. And you give them a couple of examples. And like so for hydrogen it's this, and for, you know, beryllium it's that. So they know that it's different for different elements, and they know a rough range of where it's coming from, so they have an idea of what it is. The thing they're looking at is.
>
> Then you give them the simulation, so they can look at trends in that thing. So they know what it is and when they see the numbers change they know what it means. It means it's harder to get an electron out or it's easier if you get an electron out, so they can grasp that relationship because they know what they're looking at. So the idea is they need to have the background enough to know what the data is and what it means.

Once the primary case teacher decided that students had the required background information, the GEM cycle activities with guidance strategies began.

4.8.2 The compile information and generation phases

The next two phases consisted of two closely related teacher activities: asking students to compile information between two variables using the interactive computer tools and asking students to generate a relationship between two variables based on the information they had gathered. The next two sections will describe the specific guidance strategies associated with these instructional phases.

1. **Compiling information (2:30-2:45 pm).** After providing content information, the primary case teacher typically asked students to work in pairs or groups of 3 (mode 5 in the classroom observation rubric) to compile information from a source. The primary case teacher identified the important variables and wanted students to compile information between these particular variables in order to eventually generate a pattern or relationship between them. The sources of information included classroom handouts, overheads, lists, or the interactive computer tools. The interactive computer tools were observed to be the major source of information for students in the primary case. When

the interactive computer tools were used, the primary case teacher demonstrated the software inputs (variables) and outputs (graphs or animations) by selecting and manipulating the variables and describing the x and y axes on the graphical outputs. The primary case teacher could constrain the variables that were tested using the computer tools. Transcript evidence of the primary case teacher asking students to compile information between two variables in order to construct a relationship is presented below.

> Eg. Lesson 2.
> T "Play, observe, write down what you observe [using Coulomb's Law simulations], come up with the rules. Who can tell me the relationship between distance and the electrostatic force?"

> Eg. Lesson 8.
> T demonstrates the Phases of the Elements simulation. T "What are the trends that occur as you increase temperature for the phases of the elements [on the simulation]?"

During the compile information phase of the GD approach, the primary case teacher was observed asking students to compile information between two variables that were identified by the primary case teacher. The primary case teacher usually asked students to refer to Chemland to compile information. The primary case teacher supported this activity by guiding students through the Chemland simulation software by selecting the variables and displaying the output. Thus, demonstrating the Chemland software, selecting the variables and displaying the output were considered to be guidance strategies that were coupled with the teacher asking students to compile information between two variables in order to generate a relationship.

2. Teacher guiding student construction of relationships (2:45-3:00 pm). The majority of the next block of 15 minutes was spent in some form of discussion in the primary case: either whole class (mode 3), small group (mode 5), or less frequently, lecture discussion (mode 2) according to the classroom observation rubric. It was during this period that the primary case teacher asked students to find the trends between two variables after compiling enough information. The primary case teacher was observed supporting students with finding the trends or generating a relationship between two variables with 4 specific guidance strategies. The teacher guidance strategies observed to support the activity of generating relationships were:

- "the extreme case";
- "incremental values";
- "why";
- "the comparison".

Transcript evidence of primary case teacher's guidance strategies during the generation phase are listed below for 3 categories of guidance strategies: the extreme case, incremental values, and the comparison. The guidance strategies are underlined.

<u>The extreme case.</u> The extreme case was evidence of instructor actions to promote the examination of an extreme case that may or may not be relative to a series of cases. We observed this guidance strategy being employed by the primary case teacher during the generation phase with words such as, "bigger", "most", and "last" to refer to an extreme case in relation to a series of cases. Transcript evidence of the classroom observations suggested that the use of these words by the primary case teacher was to promote the examination of an extreme case in order to help students generate a relationship between two variables.

> Eg. Lesson 3.
> <u>T Which one is a bigger jump and why?</u>
> S14 2p to 3s is 5x and 3s to 3p is 2x
> S15 Why?
> T Electrons in the 2p orbital are held more tightly [by the nuclear charge] so it's a bigger energy to take out an electron from this orbital than the 3 s orbital [which is further away].

Eg. Lesson 5.
T Think about how you can make <u>the most polar bond.</u>
What's the most polar bond you have found so far?
S1 Chlorine and aluminum. Cl is the most electronegative or polar.
T States formal definition of polarity.

Eg. Lesson 8.
<u>T What are the last two elements to melt?</u>
S C and W.
T Used for?
S Light bulbs.
T What is the trend from Cs to Hg?
S Use phases of the elements animation to provide a series of melting points.
T Plots these melting points vs. Group # to produce an inverse parabola: Cs, W, Hg.
T Why is there a peak? Using electron configurations, what orbitals are being filled?
S 6s.
T Fills in energy levels for Ir $6s^2 5d^7$. {6s is before 5d} but in W, $5d^4 6s^2$. There's no easy way to figure out the trend, so we use metallic bonding to explain this. T launches into content on Molecular Orbital Theory.

Eg. Lesson 9.
T asks students to go to Heats of Reaction simulation. What does it take to give you an endothermic versus exothermic reaction? Does anyone have a trend?
S1 Weak + weak leads to a strong exothermic reaction.
T Endothermic reaction?
S1 strong + strong leds to weak/medium reaction.
<u>T I'm just looking for extremes.</u>
T Can you deduce an equation for this? Draws delta Hrxn= (change in heat of reaction) on the board.
S2 If you are going to give energy, I am trying to think of this on the molecular level.
T How would you add up the "D's".
S3 ED reactants-ED products.
T (bonds broken)-(bonds made). There is a pictorial way of looking at this (see notes for picture). So you can use this imaginary mental picture to estimate the delta H's. This is not how it's done in reality. This is half of what helps us control reactions. It can also help us explain hurricanes. H_2O (l) → H_2O (g) Delta H equals? Is that endothermic or exothermic?

During the generation phase of the GD approach, the primary case teacher was observed asking students to find the trend between two variables. Asking students to generate a relationship was observed to be coupled with teacher actions to promote the examination of an extreme case. Thus, extreme cases were considered to be a guidance strategy that was coupled with asking students to find the trend between two variables during the generation phase of the GD approach.

Incremental values. Incremental values were defined as evidence of instructor actions to promote or model the generation of a semi-quantitative relationship or a quantitative relationship using incremental values.

Lesson 2.
T Try to double the distance and see what happens.
S2 It's $d^{2.}$
T Now look closely between the magnitude of charges and what the force is.
S3 It changes in increments.
T What do you see?
S4 When the charge goes from –1 to –2, the force doubles.
T From –2 to –3, does it double again? Go on and make changes to the simulation.
T It is going up in multiples of 1.4. Therefore force is directly proportional to charge 1 times charge 2 over d^2 (written as an equation on the board). The larger charges, the stronger the force. The larger the distance, the weaker the force.

Eg. Lesson 10.
T Relates mass and velocity using the equation: $KE=1/2mv^2$.
T Why does the lighter element go faster?
S Takes less energy to move something lighter further.
T Keep picturing molecules; let's talk about an ideal gas. Provides definition. Think about pressure. Draws a container and says, these particles are going to collide with the container. Pressure is proportional to number of collisions with walls of the container. We are going to talk about volume, T, n. What will happen to number of collisions if I double the number of moles?
S Goes up.
T By a factor of 2. Give me a relation between pressure and moles.
S P is directly proportional to number of moles.
T Temperature increases?
S Average KE increases which means the molecules are bounding off the walls more often.
T What is the relationship?
S Pressure is proportional to T.
S As volume increases, pressure goes down.
T P is inversely proportional to v.
T Now we could put all of these together into one mathematical expression.
T PV is directly proportional to?
S PV is directly proportional to nT.
T PV = nRT (introduces the gas constant).

During the generation phase of the GD approach, the primary case teacher was observed asking students to find the trend between two variables. Asking students to generate a relationship was observed to be coupled with teacher actions to promote or model the generation of a semi-quantitative relationship or a quantitative relationship using incremental values. Thus, the use of incremental values by the primary case teacher was considered to be a guidance strategy that was coupled with asking students to generate a relationship during the generation phase of the GD approach.

The comparison. The comparison was defined as evidence of instructor actions to promote making a comparison between data in order to generate a relationship. Evidence of instructor actions to promote making a comparison are underlined in the transcripts below:

> Eg. Lesson 5.
> T What kind of molecule would be non-polar? <u>What are the common features?</u>
> S6 In polar molecules, not all 3 are the same (referring to central atom and two adjoining atoms).
> T Different electronegativities will lead to different length dipoles. Need some kind of asymmetry. What is non polar?
> S7 Symmetrical molecules.
>
> Eg. Lesson 10.
> T <u>Let's compare</u> different gases (using the Boltzmann Distribution simulation). What is the reason why He is different from O_2?
> S Size and weight.
> T What is the trend?
> S He is lighter.
> T Therefore, moving?
> S Faster.
>
> Eg. Lesson 8.
> T gives them content background on Molecular Orbital Theory first and students arrive at the atom contributes 6 orbitals. Introduces metallic bonding simulation. Select Cs (6s25d10). How many valence e-?
> S 1.
> T What fraction of the band is filled?
> S 1/12.
> T Go across from left to right. Helps students to fill out a banding chart (see observation notes) where students indicate <u>how much of the band is filled for Cs Ba, Hf, W, Re.</u> The T states that if they are more than half filled, then some are in the antibonding region, leading to destability and weaker bonding. T asks how much is the Ba band filled?
> S 1/6 (ie. Has 2 valence electrons/12).
> T Bonding or antibonding?
> S Bonding.
> T More bonding in Ba or Cs (which is 1/12 filled)?
> S Ba.
> S Therefore twice as many bonds so Ba ought to have a higher boiling point.
> T For Tungsten?

S 1/2 filled.
T So it has weaker bonding.
S And that means a lower melting point!

During the generation phase of the GD approach, the primary case teacher was observed asking students to find the trend between two variables. Asking students to generate a relationship was coupled with teacher actions to promote making comparisons between data. Thus, making comparisons by the primary case teacher was considered to be a guidance strategy that was coupled with asking students to generate a relationship during the generation phase of the GD approach.

Chemland during the compile information and generation phases. We observed two main teacher activities closely related to one another: the teacher activity of asking students to compile information between two variables, and the teacher activity of asking students to generate a relationship between the two variables based on the information they had just gathered. The teacher activity of asking students to compile information between two variables that he had identified was supported by the use of Chemland software as source of information. We observed the teacher guiding students through the use of the Chemland software by demonstrating how to manipulate the variables in order to display the output. Thus, the use of Chemland software appeared to support the activity of compiling information between two variables in order to construct a relationship.

When the primary case teacher asked students to find the trend in the data, the teacher asked students to quickly gather a large amount of information with Chemland and produce a graph of the trends. Generating a relationship between two variables was also observed coupled with 4 teacher guidance strategies: the extreme case, incremental values, the comparison, and why questions. The teacher was able to encourage students to consider extreme cases with Chemland by asking students to push the variables in Chemland to extreme temperatures or concentrations. The teacher was able to afford an incremental values guidance strategy by asking students to increase values in Chemland step by step and observe the changes to the outputs (graph). The teacher encouraged students to make comparisons between substances, molecules, or data points, and this activity was enhanced with multiple color coded representations that appeared to visually draw attention to contrasts. Thus, compiling information and generating relationships were two phases of the GD approach that were fully integrated with Chemland software. Working with Chemland may have enhanced these activities by affording the primary case teacher and students the opportunity to constrain variables, produce data quickly, generate graphical trends, push to extreme values, proceed in increments, and visualize multiple, color coded representations. Although these activities did not require this technology, the teacher was observed consistently employing the interactive computer tools to enhance GD instruction.

4.8.4 Evaluation/modification of the relationship phase

3. Evaluation and modification (3:15-3:45). Once an initial relationship was generated, the primary case teacher introduced new information. In light of this new information, students were encouraged to evaluate the logical, conceptual, or empirical consistency of the initial relationship. This phase typically lasted 15 minutes and was observed to occur in small groups culminating in a whole class discussion or just a whole class discussion. Evaluation and modification activities were observed to repeat two to three times within the span of one classroom period.

The three main teacher activities associated with this phase were: the teacher provided discrepant information, and/or the teacher provided an extreme case, and/or the teacher provided confirmatory information. Within each of these teacher activities, there was a selection of teacher questions and directives that served to guide students to evaluate the new information. The teacher questions and directives that were observed included observations of the teacher asking students, what's wrong with this, why doesn't this make sense, and why questions. We also observed the teacher asking students to predict, compare, work back from the data, gather more information, see if it holds true, and design a new test during this phase. The three main teacher activities of providing discrepant information, providing an extreme case, providing confirmatory information are described below, and the specific guidance strategies associated with these activities are underlined in the transcripts.

Discrepant information. Discrepant information was described as evidence of students encountering anomalous information in reference to what they already know. Evidence of the teacher activities to provide this discrepant information and guide the evaluation of discrepant information is reported below.

Eg. Lesson 2.
T Draws a cloud picture of Mg^{24} and says what's wrong with this picture based on Coulomb's Law?
S1 Why don't electrons pull into the protons?
S2 Is the distance between the electron cloud and nucleus set?
S1 We learned it as rings, remember? What doesn't make sense?
S6 Some electrons should be at different places like a p orbital.
S7 Why don't electrons collapse into the nucleus?
T Electrons are always trying to get closer to the nuclei. Always.
S8 What is between the cloud and the nucleus?
T Mostly a vacuum. Another glaring problem!
S9 Why do all the protons stick together in the nucleus?
T What holds the nucleus together?
S10 Strong force.
T The strong force operates only at close distances unlike electrostatic forces, that works at long distances, keeping protons together. [Shows a plot of stability vs. distance which indicates that net forces cancel each other].

Eg. Lesson 3.
T What's wrong with this configuration (shows electrons with same spin in same subshell)?
S2 Same m_s.
T Why is it less favorable than (shows an orbital energy diagram with two electrons, same spin in two subshells at the lowest energy level and then at a higher energy level, two electrons, opposite spins, same subshell)?
S3
S4
T But why?
S5 Going in the same direction?
T Repulsive interaction! [Shows an additional example of two electrons, opposite spins, different subshells and places in the middle of the orbital energy diagram.] The two with the same spin in two subshells are at the lowest energy

level, (ie. most energetically favorable because)they have the same quantum numbers. These will stay further apart. This rule is Hund's rule. One at a time and the same spin. Stay as far away as possible and more energetically favorable.

Eg. Lesson 2.
T Strong force of attractions plus the electrostatic force of repulsions gives nuclear stability. He^2 has two protons and two neutrons and two electrons so we say that it has 4.00 atomic mass units but experimentally, He is 4.003. This difference in mass has been converted to energy. $E = mc^2$ and that is the net stability of the atom.
T What's more stable? 3 ^4He or 1 ^{12}C?
[S do calculations]
[T asks for a vote/polls class]
S11 ^{12}C because the lower the energy, the more stable.
S12 3 ^4He because He is a noble gas so it would be more stable.
T We are talking about nuclei. The greater the mass loss, the greater the stability.

Lesson 3.
T Spend a few minutes looking for the anomalies [using electron configuration simulations as a database]. Find the exceptions to the rules.
S6 The two anomalies are Cu, it fills up 4s to 3d, and Cr.
T When you go to higher quantum numbers, the orbital energies of the subshells decreases. Why I don't know, but more are found further down the periodic table.

Eg. Lesson 5.
T Go to the cache system and look at the dipeptide molecule. Look at the bond angles and the bond length. Look at resonance structure. See if you can find it. What would be the bond angle that you would predict for resonance structure 1, resonance structure 2?
S10 The unbonded pair would be <109 vs. Resonance structure 2 > 109.
T What was our rule from last time?
S11 4 things are 109, 3 things are 120 (things=bonded atoms and lone pairs).
T That's a big hint. What do you see in the dipeptide?
S13 120 but it has three things.
T That is evidence of the partial double bond character.

Eg. Lesson 6.
T provides an example of an orbital energy diagram of F_2 showing a single electron available in each 2 p orbital allowing a linear geometry. Then teacher draws hybrid orbitals of H_2O showing a tetrahedral geometry. [What would the bond angle be] if you used 2 2p orbitals?
S5 109.5?
T It is the angle in H_2O, but it's not [what one would expect] in H_2O.
S6 90 (is the angle you would expect).
T CH_4 where 3 of the bonds are made with 2p orbitals and one with 2s [according to Valence Bond Theory], but how can it be a straight tetrahedral [all equivalent at 109.5]? So we have a problem for which has led to "hybrid orbitals"; that is, atomic orbitals mix or hybridize leading to hybrid orbitals. So

in the case of CH_4, we have 4 sp3 orbitals which are equivalent and form the correct geometry (tetrahedral-all 109.5).

Eg. Lesson 7.
T Shows an animation of a peptide bond (=C-N-C) and states that you expect a tetrahedral arrangement about the nitrogen <u>but actually get trigonal planar</u> (120). <u>Why do we get trigonal planar instead of tetrahedral?</u>
S5 A chemical reaction?
T Builds a model for students which uses a double bond between N and C but no twist unlike the allene model which had a twisting about the C shown just prior. <u>Why does this violate our allene type model (C=C=C)?</u>
S6 Because you can't bond a carbon to oxygen [referring to peptide bond] and a carbon to a nitrogen. Can't both pi bond.
T Need a resonance structure. C-N vs C=N. It's partially this and that [referring to both resonance structures], but the reason N is flat is because it's more stable [ie. Because it is a resonance structure, there is little twisting since the electrons that make up the pi bond are delocalized over O,C, and N compared with allene where the pi bond (which occurs between two p orbitals that are parallel II to one another) is only at one end of the molecule].

Based on the classroom observations in the primary case, it appeared that when discrepant information was provided by the teacher, the teacher also asked, "what's wrong, what doesn't make sense, and why" questions, or asked students to predict or compare with this activity. These questions and directives by the teacher were considered guidance strategies that we observed with providing discrepant information.

<u>The extreme case.</u> The primary case teacher was also observed providing extreme cases. An extreme case was described as evidence of instructor actions to promote the examination of an extreme case that may or may not have been relative to a series of cases. We observed this guidance strategy being employed by the teacher during the evaluation and modification phase with words such as, "bigger", "most", and "last" to refer to an extreme case in relation to a series of cases. Transcript evidence of the classroom observations suggested that the use of these words by the teacher to promote the examination of an extreme case was employed in order to help students evaluate a relationship between two variables.

Eg. Lesson 2.
T [from an overhead], between you all, what element has the largest number [ie. Nuclear stability]? It turns out that Fe is the most stable. [T provides an equation for determining the most nuclear stable]. Why is it that when you get past Fe, it gets less stable?
S14 Aren't these elements radioactive?
S15 The greater the mass loss up until Fe, the greater the stability but after Fe, the less the mass loss, the less stable.
S19 [Because] as you put nuclei together, the strong force works, but when the nucleus becomes too big, repulsions start having a greater effect than the strong force.

Eg. Lesson 3.
T Puts Coulomb's law on the board: PE is directly proportional to charge1xcharge2/radius. Go to Chemland's orbital energies. What happens to the energies as you go right across a period and all the way down?
S7 The orbital energies get lower as you go across.
T What happens as you go down?
S7 The orbital's energy goes down?
T But the energies are going up! Why is that?
[S discussion in groups ensues]
T Why? Think about the charge to charge interaction with the nucleus?
S8. As you go across the table [periodic table], aren't the orbitals getting bigger, that is, they have more electrons?
T Is the radius going up? Think of effective charge.
S9 Well, there may be electron shielding as you further across [the periodic table]. There are more protons too and that leads to a higher Zeff . So there are more protons, the electrons are held more tightly.
T As you go down , the orbitals are larger and as you go across, the electrons are held more tightly and are closer to the nucleus here. What trends do you expect as you go down and across and why? I want you to understand the relationship between these sizes and these properties.
S10 As you go down the periodic table, the atomic sizes get larger, as you go across, there are more electrons here but there are more protons so the electron's are drawn in and that's why these are smaller.

During the evaluation and modification phase of the GD approach, the primary case teacher was observed providing information to the students. In some cases, the information was an extreme case (largest, lowest, smallest). The teacher acted to promote the examination of an extreme case by asking students to consider new variables; asking students why questions, or asking students to make comparisons. Thus, new data variables, why questions, and comparisons were considered guidance strategies that we observed coupled with providing an extreme case during the evaluation and modification phase of the GD approach.

Confirmatory information. The primary case teacher was observed using cases that confirmed an initial relationship as a means of further evaluating the relationship.

Eg. Lesson 3.
T Which radius would you expect to be smaller? The radius of the Mg cation vs radius of the atom and the radius of the chloride anion vs the radius of the chlorine atom?
S11 The radius of the Mg cation is smaller and the radius of chloride is bigger.
T presents an isoelectronic series of O^{2-}, F-, Ne, Na^+ Mg^{2+} and says which do you expect to be the largest?
S12 O^{2-} because they have the same number of electrons with a different nuclear charge [confirming initial relationship].
T Yes. Because Mg^{2+} has a higher number of protons and a smaller radius.

T uses an overhead to show a plot of ionization energies as you move from Be to O. Across the periodic table, ionization energies are getting larger but.
T Explain why ionization energies are getting larger and why is it not a smooth increase? [plot of IE shows a jagged staircase].
S16 2p3 for nitrogen vs. 2p4 for O.
T This is not a chemists game. We have observable evidence. Be to B?
S17 B is starting a new orbital system at a slightly higher energy (ie. Be 2s2, B 2s2 2p1 so it's easier to pull off an electron here so ionization energy goes down even though going across the row) [this experimental evidence confirms the theory of energy levels [ie. 2s1, 2p2].

The series of cases presented by the teacher did not disconfirm the initial relationship but confirmed the relationship. The guidance strategies that we observed associated with providing information that confirmed included making comparisons, making predictions, asking why questions and asking students to find more information.

Adding new content information. Throughout the evaluation and modification phases of the GD approach, the primary case teacher was observed adding new content information. Adding new content information was defined as instructor actions to provide field-specific content information.

Eg. Lesson 2.
S7 Why don't electrons collapse into the nucleus?
T Electrons are always trying to get closer to the nuclei. Always.
T What holds the nucleus together?
S10 Strong force.
T The strong force operates only at close distances unlike electrostatic forces, what works at long distances, keeping protons together. [Shows a plot of stability vs. distance and indicates that net forces cancel each other].

Eg. Lesson 5.
T <u>Provides content information about miscibility.</u> Why are polar/polar interactions good?
S3 Because opposite poles attract.
T Yes. If you have greasy hands, what molecule do you use to take it off your hands?
S6 Polar?
T No [discusses properties of molecules]
S7 Polar and non polar.
T Got there. Why?
S7 Need both polar and non polar ends.
S8 Like in soap.
S9 And phospholipids.
<u>T Discusses detergents.</u>
S3 How can you have a polar end and a non-polar end?
<u>T Discusses greasy tails, hydrophilic, hydrophobic.</u>

Adding new content information was observed during the evaluation phase of instruction and was included as a guidance strategy that was coupled with all three teacher activities during the evaluation and modification phase.

Thus, the evaluation and modification phase of the GD approach consisted of 3 observable teacher activities: providing discrepant information, providing the extreme case, or providing confirming cases. We detected that the teacher activities were coupled with 10 different guidance strategies. The specific guidance strategies included: asking students to make comparisons, consider new variables or new data points, make predictions and asking students why questions to name a few. The primary case teacher was also observed adding new content information during the evaluation and modification phase of the GD approach to instruction.

<u>Chemland during the evaluation and modification phase.</u> Throughout the evaluation and modification phase, we observed three main teacher activities: providing disconfirming information, providing extreme cases, and providing confirming information. These activities were coupled with teacher guidance strategies such as: making comparisons, asking why questions, asking what's wrong questions, making predictions, considering new data points, designing a new test, see if it holds true, finding more information and adding content information. The teacher activities and guidance strategies were fully integrated with the use of Chemland software. We observed that the primary case teacher asked students to select different variables and control for others in order to design new tests, or push variables to extreme temperatures or concentrations. We also observed the primary case teacher asking students to gather more information quickly and dynamically regenerate graphs. We also observed the primary case teacher referencing the animations at the molecular level and asking students to compare color coded curves on the graphs. Thus, the use of Chemland software appeared to support the activities of evaluating new information.

The teacher activities, coupled with guidance strategies and the use of interactive computer tools are represented diagrammatically in Figure 4 on the next page.

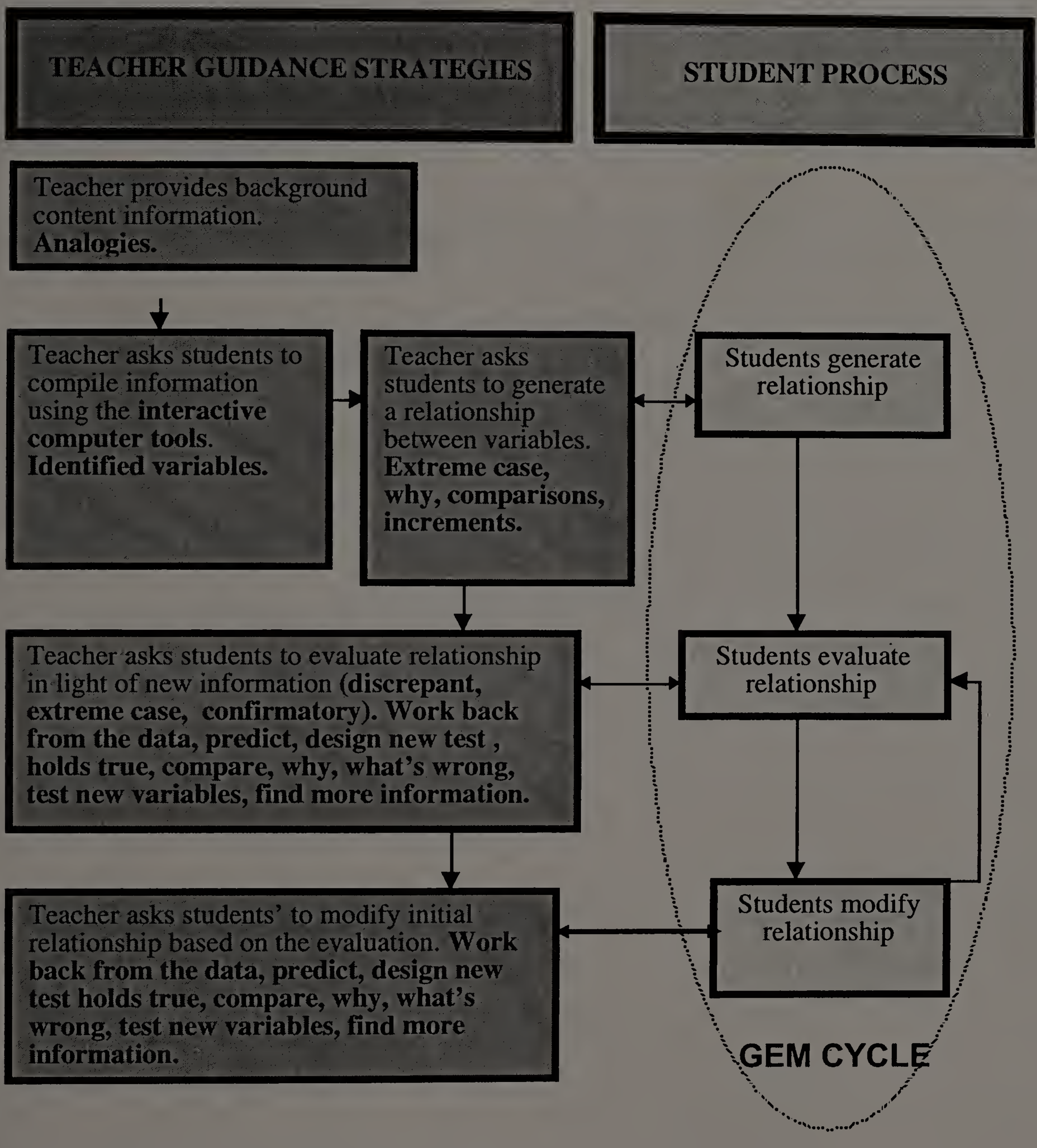


Figure 4. Teacher guidance strategies embedded in the guided discovery (GD) approach.

4.8.5 Summary of the guided discovery (GD) approach

An initial test of scientific inquiry skills uncovered that students enrolled in a introductory chemistry class produced the most significant gains after class instruction compared with introductory chemistry courses at this institution and introductory science courses at two other university institutions. The purpose of this section was to describe the instructional strategy in this class to eventually understand how it may have contributed to the gains in inquiry skills that emerged on the initial test. This introductory chemistry class was referred to as the primary case.

After three semesters of classroom observations (20 classes observed) of the primary case, a consistent pattern of instruction emerged. The teacher in the primary case was observed using a "guided discovery approach" with interactive computer tools or a GD approach to instruction. The GD approach consisted of four phases of instruction: background information, compile information, generate a relationship, and evaluate and modify the relationship. Each phase was characterized by the following teacher activities. During the background information phase, the teacher was observed providing initial content information. During the compile information phase, the teacher typically asked students to compile information between two variables from the interactive computer tool, Chemland, and immediately afterwards, during the generate relationship phase, the teacher asked students to find the trend in the information they had just gathered. After generating a relationship between two variables, the teacher was observed triggering an evaluation and modification of the initial relationship by providing new information from the interactive computer tool. This information was observed to be discrepant information, an extreme case, or confirmatory information. Evaluation and modification of the initial relationship was a phase of instruction that was observed repeatedly. The generation, evaluation, and modification of relationships in chemistry was referred to as GEM, and because the evaluation and modification of teacher activities were observed repeatedly, cycles of GEM were reported within the GD approach. Peer review of classroom video and co-observations of the classroom using the classroom observation rubric further confirmed the identification of these cycles within the GD approach to instruction in the primary case. Thus, the instructional strategy in the primary case, referred to as the "guided discovery approach" with interactive computer tools or simply, the GD approach, contained four main phases of instruction that appeared to trigger iterations of GEM cycles.

These GEM cycles were detected on average, twice per class in the primary case. Student data from the CAT post- surveys (n=22) further supported the classroom observations that GEM activities were happening within the primary case, and with greater frequency in this class than other classes:

1. Fully 100% of surveyed students in the primary case (n=22) agreed that, "There are more frequent opportunities to generate scientific ideas in this class than most other classes."
2. 81% of surveyed students agreed in the primary case (n=22) that, "I am asked to challenge or evaluate a scientific idea more often in this class than my other classes."
3. 95% of surveyed students agreed in the primary case (n=22) that, "I have been asked to construct explanations about scientific information that was presented in a computer simulation."

GEM cycles were detected 52 times in the course of one semester in the primary case, despite the different topics in the syllabus that were covered throughout the introductory chemistry course.

Associated with the teacher activities in the primary case were specific guidance strategies. Over 15 guidance strategies were identified and documented during GEM cycles. For example, during the generation phase of instruction, the primary case teacher was observed asking students to compile information and generate relationships between two variables. This phase of instruction was associated with the specific teacher guidance strategies: the extreme case, incremental values, why questions and the comparison. Once an initial relationship was generated, an evaluation and modification of the initial relationship was pursued. The evaluation and modification phase of instruction consisted of teacher activities such as providing discrepant information, the extreme case, or confirming cases. The guidance strategies the teacher used during this phase included asking students to make comparisons, asking students to make predictions and asking students for an explanation or why questions. The teacher was also observed asking students to consider new variables, design new tests, or gather more information during this phase of instruction. It was noteable that the teacher did not initially "correct" students misconceptions or suggest crucial tests. Thus, specific teacher guidance strategies were coupled with teacher activities to trigger GEM cycles within the GD approach to instruction.

Interactive computer tools were observed to be fully integrated into all phases of the GD approach to instruction. According to the primary case teacher,

> A lot of the kinds of things we do with computer simulation could be done with pieces of paper. The thing that's better about the computer part of it is, you can do a lot more exploring, so it gives [students] more control over what they're going to look at, as opposed to if I give them a sheet of paper with numbers on it. It's like I'm going to look at this information, I'm going to come to some conclusion, I'm going to look at some more information, and I'm going to test those conclusions.
> That all works the same way, but [with information already on a sheet of paper] it's not them going and choosing what to look at.
>
> [S]o if I can say, '[L]ook at trends across a period in a periodic table, they [the students] can pick what period they want to use. And that might seem trivial, but it's kind of an ownership thing on their part-- that they are doing the exploring as opposed to I'm exploring for them and asking them to conclude [based] on my exploring. So when I throw up an overhead, I'm doing the exploring and they [the students] are

explaining it. And that's okay, but when it's a simulation and they are choosing things, then they are doing the exploring much more. So it's a control issue.

The primary case teacher was consistently observed referring students to Chemland software during GEM cycles. For example, during the compile information phase, the primary case teacher asked students to compile information between two variables with Chemland. Chemland not only afforded as a large source of information quickly during the compile information phase, but the teacher could constrain the number and type of variables students worked with by using the Chemland software. During the generate relationship phase, the primary case teacher asked students to find a trend based on the information they had gathered using Chemland graphs. When the primary case teacher and students entered the evaluation and modification phases of the GD approach to instruction, the primary case teacher was observed providing new information from Chemland and asking students to push variables to extremes, or design new tests and regenerate graphs quickly. Thus, Chemland was observed to be fully integrated into the GD approach and it appeared that the instructor used these interactive computer tools to facilitate the generation and evaluation/modification (GEM) of relationships in chemistry.

The classroom observations of the primary case uncovered a pattern of instruction termed the guided discovery (GD) approach, where the primary case teacher was observed asking students to generate, evaluate, and modify relationships in chemistry. The GD approach to instruction was observed to be sustained throughout the semester in the primary case and was characterized by GEM cycles, teacher guidance strategies and the full integration of interactive computer tools.

4.9 Lecture 1 and 2 approaches to classroom instruction

4.9.1 Lecture 1 and 2 classes

An initial test of scientific inquiry skills uncovered that students enrolled in an introductory chemistry class (the primary case) produced the most significant gains after class instruction compared with lecture 1 and lecture 2 introductory chemistry classes on an intial test. The purpose of this case study was to analyze the instructional strategy and interactions in the primary case to understand how it may have contributed to the gains in inquiry skills that emerged on the test. Classroom observations of the primary case were conducted in order to identify the instructional strategies in this class.

In addition, the lecture 1 and lecture 2 classes were also observed. The two contrasting cases of more "traditional" chemistry instruction in introductory chemistry at the same institution were included to place the instructional strategies of this primary case into context. Although lecture 1 and lecture 2 covered the same syllabus and were offered at the same institution as the primary case, they were different in many other aspects—including approaches to instruction. The inclusion of lecture 1 and lecture 2 in the study was not intended to serve as a controlled comparison to the primary case; rather, the purpose of including descriptions of lecture 1 and lecture 2's approaches to instruction was as an attempt to acquire initial data on the question of whether the primary case teacher's methods departed in a significant way from the normal teaching methods used in the chemistry department. This section outlines the instructional strategies of the two contrasting cases (lecture 1 and lecture 2).

The learning environments of the three classes of an introductory chemistry course at this institution shared some similarities, but also had some important differences. All three introductory chemistry classes shared a common syllabus and common classroom resources such as the text, the CRC, and the OWL homework system. The students in these three classes also reported similar prior experiences in science and self- perceptions of their persistence and abilities on the CAT pre-survey that was given to students enrolled in these three classes at the beginning of their class semester. All of the teachers received positive student evaluations and shared similar content and process goals for their students.

The three classes, however, were different in a number of respects. The lecture classes had larger classroom sizes and were in large lecture theaters. The electronic classroom was equipped with 26 computers, whereas the lecture classes were equipped with a single demonstration computer. More students enrolled in the lecture classes reported less interest in chemistry on the CAT pre- survey. All of three classes also had different teachers. The primary focus of this study, however, was not on these specific differences between the classes, but on their different approaches to instruction. The additional two classes were included as part of this study to provide a sample of other approaches to instruction in introductory chemistry in this department. Any comparisons that were made were not as a controlled experiment, but as an attempt to acquire initial data on the question of whether the primary case teacher's methods departed from the other teaching methods used in the chemistry department.

The lecture classes were observed 6 times in total with the classroom observation rubric, and a central pattern of instruction in these classes emerged that was markedly different from the primary case. Typical lessons, comparing topics, and comparing classroom observation rubrics highlighted the differences in the instructional approaches between the primary case and lecture 1 and the primary case and lecture 2.

4.9.2 Patterns of instruction in lecture 1

<u>Transcript of a classroom observation of a lesson in Lecture 1.</u>

T How do we know we have a chemical reaction?
S3 Heat and light.

S4 Matter changes.
T What do we mean by changes?
S Transforms.
Substances displayed on bench top. Burning paper demonstration here.
T Explains that matter transforms but we don't lose matter.
T Can we get more precise? Demo breaks chalk. Tell me about the two pieces.
S5 It's the same.
S6 The atoms are arranged with the same relationship to each other on the particle level.
T Same chemical composition. The important point is that in a physical change is that you will have the same chemical composition.
T Introduces isotopes. Why do they have more neutrons than protons?
S Explains neutrons act as a buffer for protons in the nucleus from repelling each other.
T Radioactivity comes from crowding too many protons and the nucleus flies apart. Some are more unstable than others (depending on half life). Provides an example using uranium. Beyond Bi, all the elements are radioactive. What examples did I give of different chemicals? Copper and copper ion? Holds up a chunk of copper. We looked at the periodic table. There's a structure to it. Draws a table on the board.
S3 Who decides on where the staircase is?
T Chemists have some disagreement on this.
Shows materials. What makes a metal a metal and a non-metal a non-metal?
S11 How they are combined chemically?
T Can we go deeper?
S12 Willingness to donate or accept electrons. Stable octet.
T Metals give off electrons and non metals take electrons. The electron tells us the chemistry. This is the key point.

Pattern of instruction in lecture 1. Three fifty minute lessons of lecture 1 were observed in this class, one in September, one in November, and one in December. According to the classroom observation rubric, the most common method of instruction was 2, lecture discussion. Lecture discussion remained consistent throughout all of the lessons observed. Out of the three lessons observed, the lecture 1 instructor always began with a definition. The lecture 1 instructor then constructed a list or a comparison chart, from where students from the lecture 1 class grouped together similar chemical processes in order to distinguish them from others. The lecture 1 instructor may have followed with demonstrations and relevant examples. If the lecture 1 instructor introduced a problem to students, the lecture 1 instructor provided the formulas, modeled how to do the problem once and then asked students to apply the problem solving strategy to several examples as a whole class or as individuals using a handout. The central pattern of instruction in the lecture 1 class could be depicted as:

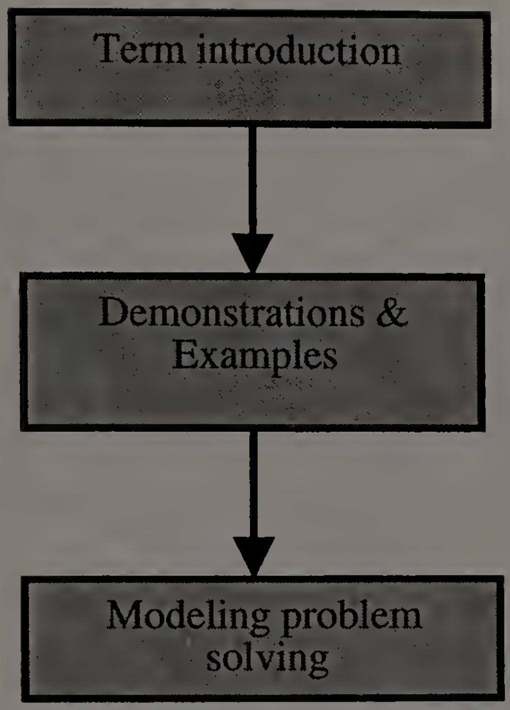


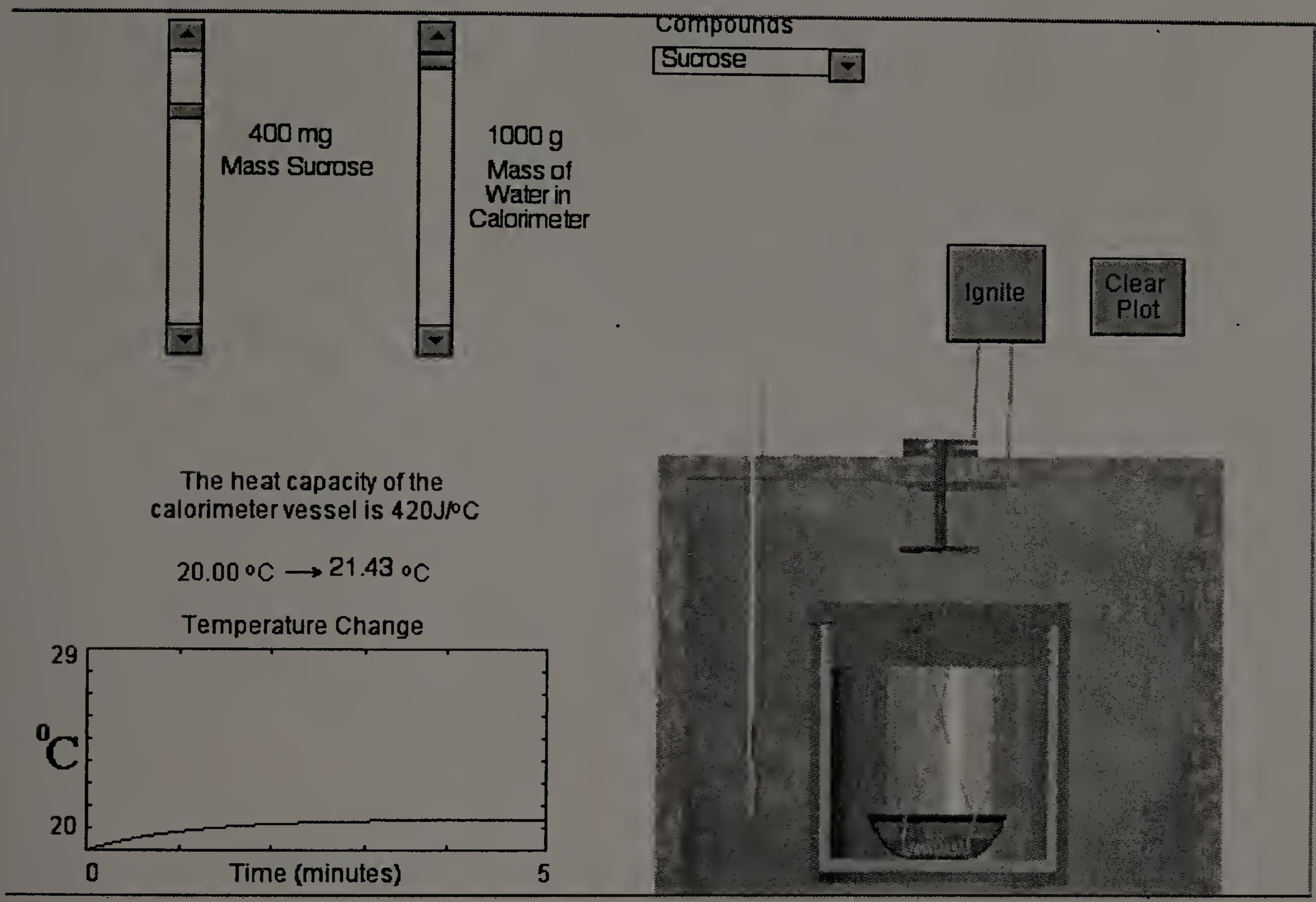
Figure 5. Pattern of instruction in lecture 1.

4.9.3 Contrasting the primary case with lecture 1

Table 22. Contrasting heat calorimetry.

Primary case	Lecture 1
T asks students to go to Calorimetry simulation. Figure out what effect does the mass have on heat capacity. Generation S Use calorimetry simulation here and gather information. T The less water [in the calorimeter], the bigger the S Change. Generation T Why? S Less to heat up. T q= mcdeltaT. Try different substances and determine change in heat where Cwater=420 J/K (referring to the calorimetry simulation). S Test different substances using sim. T What's the relationship between q reaction, q water, q calorimeter? What kind of equation might you write to relate those? E is conserved so heat has to go somewhere! S qrxn= (q water + q calorimeter) Generation T Adds negative sign in front. So now you know C water and you should be able to figure out the combustion of one of the compounds. S Do I use g or kg? T Use compatible units. S Is heat absorbed by the calorimeter? T Yes, by the walls of the calorimeter. S How does that give you q reaction? T Let's put together an equation. Q water=delta Tc water+mass water.	T How much energy is in my teaspoon of sugar? Where is it telling Energy? S Calories. term introduction T A calorimeter is used to measure the amount of energy in a substance. demonstration T Sparkly combustion demo of potassium chlorate with sugar. Writes combustion reaction of Mg. How can I measure Energy? Problem-solving S Weigh before and after combustion. T No, MgO weighs more. S Close system, heat water. T Heat given off by reaction=heat absorbed by the water. What do I need to know? S Changes in T. S Mass of water. S Specific heat.

These contrasting cases of two different ways to begin the topic of heat calorimetry highlighted several key differences between the instructional approach of the primary case and Lecture 1. In the primary case, the teacher initially asked students to work with a computer simulation of a calorimeter to discover the effects of the mass of the water on the heat of the reaction in the calorimeter. Students were observed gathering information and testing their ideas with the Heat Calorimetry computer simulation to generate a semi-quantitative relationship about the effect of the water in the calorimeter on the temperature of the system.



In order to determine that the less the water, the greater the change in temperature, students had to test different masses of water with the computer simulation and compare the resultant temperature curves on the graph. The primary case teacher asked why is there a difference in temperatures and the students suggested that there is less to heat up in the calorimeter. Thus, at the beginning of the lesson on heat calorimetry, students in the primary case were involved in testing their ideas using the interactive computer tool and comparing graphs in order to generate a semiquantitative relationship between mass of water and temperature change.

This start of the calorimetry lesson in the primary case was in contrast to the start of this lesson in the lecture 1 class. In the lecture 1 class, the lecture 1 instructor began by asking the whole class, " How much energy is in a teaspoon of sugar?" "Where is it telling energy?" A student responded with a factual answer: calories, and the lecture 1 instructor followed the student response with a definition of a calorimeter. The lecture 1 instructor defined a term instead of discussing energy with the student further.

As the lesson on heat calorimetry continued, the teacher in the primary case encouraged students to construct another piece of the relationship when he asked the students to work with the computer simulation to generate another rule about the effects of different substances on the heat of the reaction in the calorimeter. Combining these pieces (the effects of different masses of water and the effects of different substances on the heat of the combustion reaction) finally led to the construction of an overall equation for the heat of the reaction inside the calorimeter by the students in the primary case. Throughout this process, the primary case teacher in the primary case guided the students to collect information, test different substances, make comparisons between graphs, and generate semi-quantitative and quantitative relationships with the interactive computer tools.

In contrast, the lecture 1 class instructor continued the lesson with a demonstration of a sparkly combustion reaction. The demonstration was followed with a question to the whole class about how could energy be measured. One student suggested to weigh the compounds before and after combustion. The lecture 1 instructor may have interpreted this student's statement as a suggestion that the product of the demonstration combustion reaction would weigh less after it is burned than before because the lecture 1 instructor responded by stating, "No it will weigh more". Another student (who may have had some prior knowledge of calorimetry) stated,

" Close the system and heat the water". At this point, the lecture 1 instructor provided a semiquantitative relationship that represented how to measure energy. The lecture 1 instructor asked students to fill in the variables to measure energy, and students responded with the correct answers.

Comparison between the primary case and lecture 1. The primary case teacher who used the guided discovery (GD) approach initially triggered the generation of relationships about heat capacities by having students gather information, test ideas, compare graphs, and explain heat calorimetry. In contrast, the lecture 1 instructor , initially began the lesson on heat calorimetry by stating the definition of a term, conducting a combustion demonstration, and attempting to solve a problem about how energy could be measured with the lecture 1 students . The lecture 1 instructor concluded the lesson by providing a semi-quantitative relationship for the students. The approach to instruction in lecture 1 was observably different from the teaching strategies that characterized the GD approach to instruction in the primary case because there was limited evidence of the lecture 1 instructor asking students to generate relationships, and evaluate and modify them in light of new information. These differences in instructional approaches between the primary case and the lecture 1 class were further supported by student accounts of teacher activities in their classrooms in the CAT post-survey.

1. Significantly more students agreed (n=22) that, "there are more frequent opportunities to generate scientific ideas in this class than in most other classes" in the primary case than surveyed students in the lecture 1 class (n=112) ($p<0.05$).
2. Significantly more students agreed (n=21) that, "there are more frequent opportunities for students to make and test their own predictions in this class than in

most other classes" in the primary case than surveyed students in the lecture 1 class (n=113) (p=0.03).

3. Significantly more students agreed that, "I was frequently asked to analyze data from a graph or table in the class" in the primary case (n=21) than the lecture 1 class (n=112) (p=0.00).
4. Students in the primary case agreed that, "I have been asked to construct explanations about scientific information or observations during class" (n=21). There were significantly less students who agreed to this same statement in the lecture 1 class (n=113) (p=0.00).
5. Significantly more students agreed that, "I am asked to challenge or evaluate a scientific idea more often in this class than my other classes" (n=21) in the primary case than the students surveyed in the lecture 1 class (n=113) (p<0.01).

Discussion of the differences between the primary case and lecture 1. There were numerous differences between the primary case and the lecture 1 class, and one of those differences appeared to be the methods of instruction. Although both instructors shared the same syllabus and reported similar content and process goals for their students, their methods of instruction were markedly different. The pattern of instruction that emerged in the lecture 1 class could be compared with the guided discovery (GD) approach to instruction in the primary case. A linear pattern of instruction emerged from the lecture 1 class that was characterized as term introduction, demonstrations or examples, and modeling of problem solving. This approach to instruction was observably different from the GD approach to instruction. For example, when instruction on the lesson topic of calorimetry began was compared, there appeared to be a difference between introducing terms at the beginning of lecture 1 instructor's lesson on heat calorimetry and asking students to generate relationships between the effect of mass on changes in temperature at the beginning of the primary case teacher's lesson on heat calorimetry.

The approach to instruction in lecture 1 was observably different from the teaching strategies that characterized the GD approach to instruction in the primary case because there was limited evidence of the lecture 1 instructor asking students to generate relationships, and evaluate and modify them in light of new information. The differences in approaches to instruction between the lecture 1 class and the primary case persisted throughout the lesson on heat calorimetry.

These observable differences were further supported by student survey results (CAT post-survey) that suggested that there were significant differences between the methods of instruction between the primary case and the lecture 1 class. Surveyed students in the primary case (n=22) reported that there are more frequent opportunities to generate relationships and make and test predictions in this class more often than students surveyed in the lecture 1 class (n=112) ($p<0.05$). In addition, surveyed students (n=22) in the primary case reported being asked to analyze data from a graph or table, test and evaluate ideas, and construct explanations significantly more often than students surveyed in the lecture 1 class (n=112) ($p<0.05$). Lecture 1 student CAT post-survey results supported the classroom observations that the Lecture 1 instructor did not carry out a GD approach to instruction or the critical teacher activities associated with the GD approach. Thus, GD approach teacher activities such as asking students to generate, evaluate, and modify relationships, make and test predictions, or analyze graphs were not observed being implemented by the instructor in lecture 1.

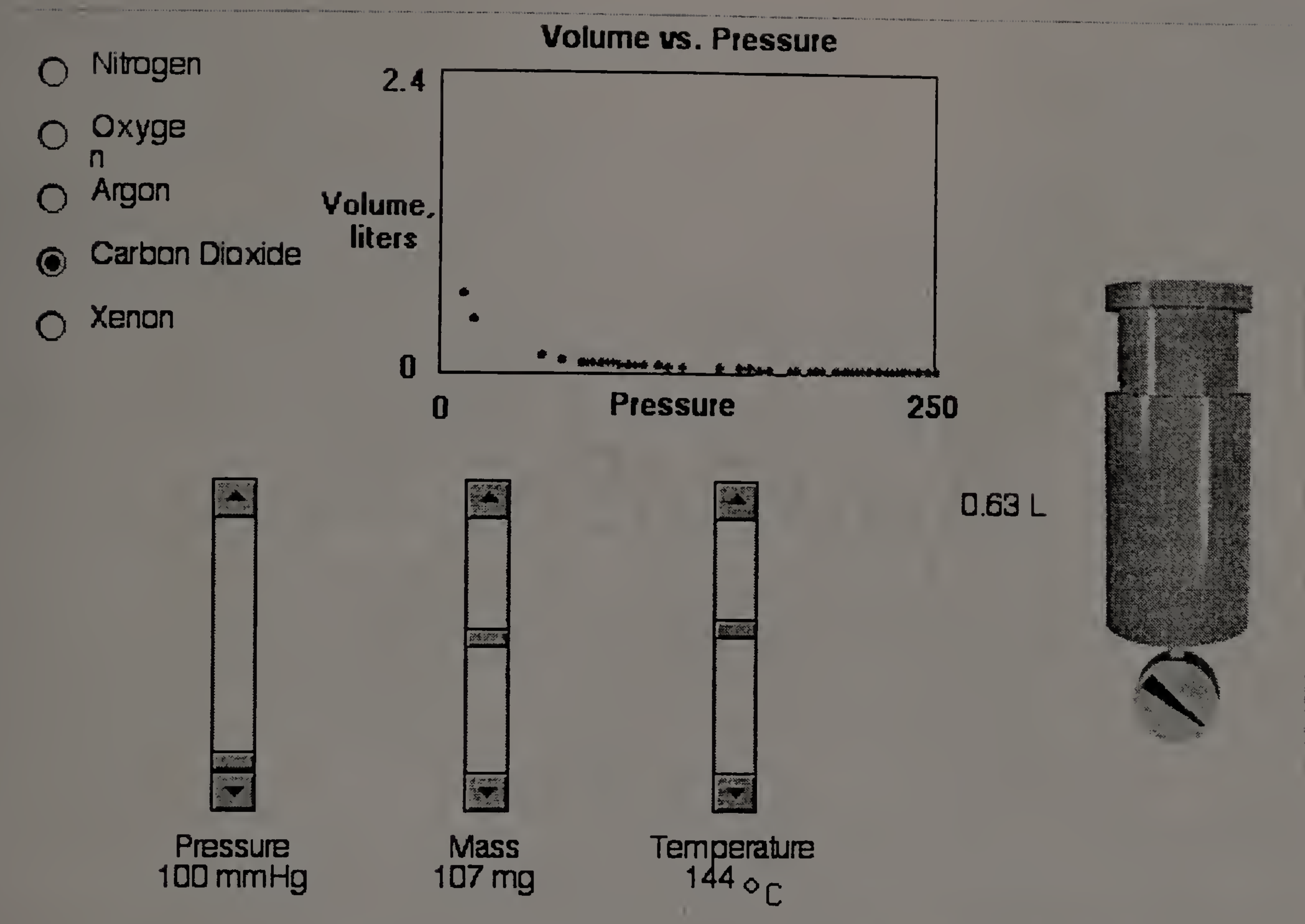
Both lecture 1 and primary case teachers were considered to be effective teachers by their colleagues and they received positive student evaluations about the learning in the classroom. Even though both teachers expressed similar content and process goals for their class at the beginning of the semester, the lecture 1 instructor did not appear to implement activities that would be considered process-oriented in the lecture 1 class. This finding was not surprising, since the lecture 1 instructor did not develop instructional strategies explicitly designed to achieve these goals at the outset. But contrasting these cases suggested, at the very least, that the lecture 1 class showed observable differences in lesson activities compared with the primary case and that led one to believe that the activities in the primary case could be considered distinctive compared with the more traditional approach to instruction in introductory chemistry that was represented by lecture 1.

4.9.4 Pattern of instruction in lecture 2

The instructor in lecture 2 had co-taught a class with the primary case teacher in order to learn the guided discovery (GD) approach using Chemland interactive computer tools. The challenge for the instructor in lecture 2 was to attempt to use the GD approach in a large lecture theater with one demonstration computer to work with Chemland instead of in the smaller, electronic classroom with 26 computer terminals.

Typical of a classroom observation of a lesson in Lecture 2. Three fifty minute lessons were observed and coded for Lecture 2. A typical example of a lesson in Lecture 2 was transcribed below:

T How do you figure out how much gas is in this room?
S Measure T, P, volume.
T We will try to come up with an understanding of T,V, P at the molecular level.
Shows an animation of a container in the Gas Laws Simulation:



T How would you figure out the volume of a container? (Waits) Measure the size. What does temperature and pressure mean? Runs simulation in demonstration mode. What's happening?
S Bouncing around. Hitting the sides.
S They exert pressure on the walls.
T How?
S Hit walls.
S Change direction.
T There must be a force exerted on it! Is the pressure constant or changing?
S answers.
T Changes depending on how many molecules hit the wall at any given time.
S Only so many molecules.
T How many moving at the same speed?
S No.
T
S Slow.
T Hotter.
S Fast. They all sped up.
T All the same speed?
S No.
T They all sped up?
S Sped up on average.
T What do you have to do?
S Add Energy.
T Heat up. Where does the energy go?
T Into gas molecules.
S Increase speed.

T Because velocity is related to kinetic energy.
S The smaller the volume, the harder it is to measure how much there is?
T Not necessarily.
T What would I change to make pressure greater?
S answers.
T What are molecules doing if I increase the kinetic energy and why?
S If they are moving faster.
T They hit the walls harder.
S And it's harder for them to turn around.
T Collisions?
S Add more molecules!
T Well more collisions changes the pressure. So changing the force of collisions or the number of collisions will change the pressure. T draws a linear volume vs. mass graph.
T If I have very little mass, what happens? Runs gas laws simulation and increases the mass. What happens if I increase the amount of gas in order to keep pressure constant?
S The volume increases.
T Increases temperature on simulation.
S Volume.
T Volume increases. Why? T provides an explanation.

<u>Pattern of instruction in lecture 2.</u> Three fifty minute lessons of lecture 2 were observed: one in September, one in November, and one in December. The most common method of instruction for lecture 2 was lecture discussion, followed by whole class discussion, and lecture modes, according to the classroom observation rubric. The lecture 2 instructor began instruction by introducing a representation of a model or simulated lab results with Chemland at the front of the classroom in demonstration mode. Transcript from a lecture 2 lesson:

> T How do you figure out how much gas is in this room?
> S Measure T, P, volume.
> T We will try to come up with an understanding of T,V, P at the molecular level. <u>Shows an animation of a container.</u>
> T How would you figure out the volume of a container? Measure the size. What does temperature and pressure mean? Runs animation. <u>What's happening?</u>
> S Bouncing around. Hitting the sides.
> S They exert pressure on the walls.

Based on the model, the lecture 2 instructor would ask the whole class questions about the parameters of the model.

> T <u>What would I change</u> to make pressure greater?
> S answers.
> T What are molecules doing <u>if I increase</u> the kinetic energy and <u>why</u>?
> S If they are moving faster.
> T They hit the walls harder.

S And it's harder for them to turn around.

The interactions would typically lead to the generation of the chemical relationship.

T Well more collisions changes the pressure. <u>So changing the force of collisions or the number of collisions will change the pressure. T draws a linear volume vs. mass graph.</u>

If time was available, an opportunity for the lecture 2 instructor to evaluate and modify the relationship with the students was also observed. This pattern of instruction in the lecture 2 class could be depicted as: Teacher demonstrates the model (modeling kits, graphs, diagrams) →Teacher demonstrates changes of parameters (increase, decrease, how and why)→Generates the relationship (via teacher question/student answer), Evaluate, Modify.

4.9.5 Contrasting the primary case with lecture 2

<u>The primary case and lecture 2.</u> The central pattern of instruction in lecture 2 could be compared with the phases of instruction leading up to generating the relationship in the primary case. The classroom observations of the remainder of the instructional cycle in lecture 2 revealed that the lecture 2 instructor asked students to evaluate and modify relationship. Contrasting instruction in the primary case and lecture 2 is depicted in the figure below.

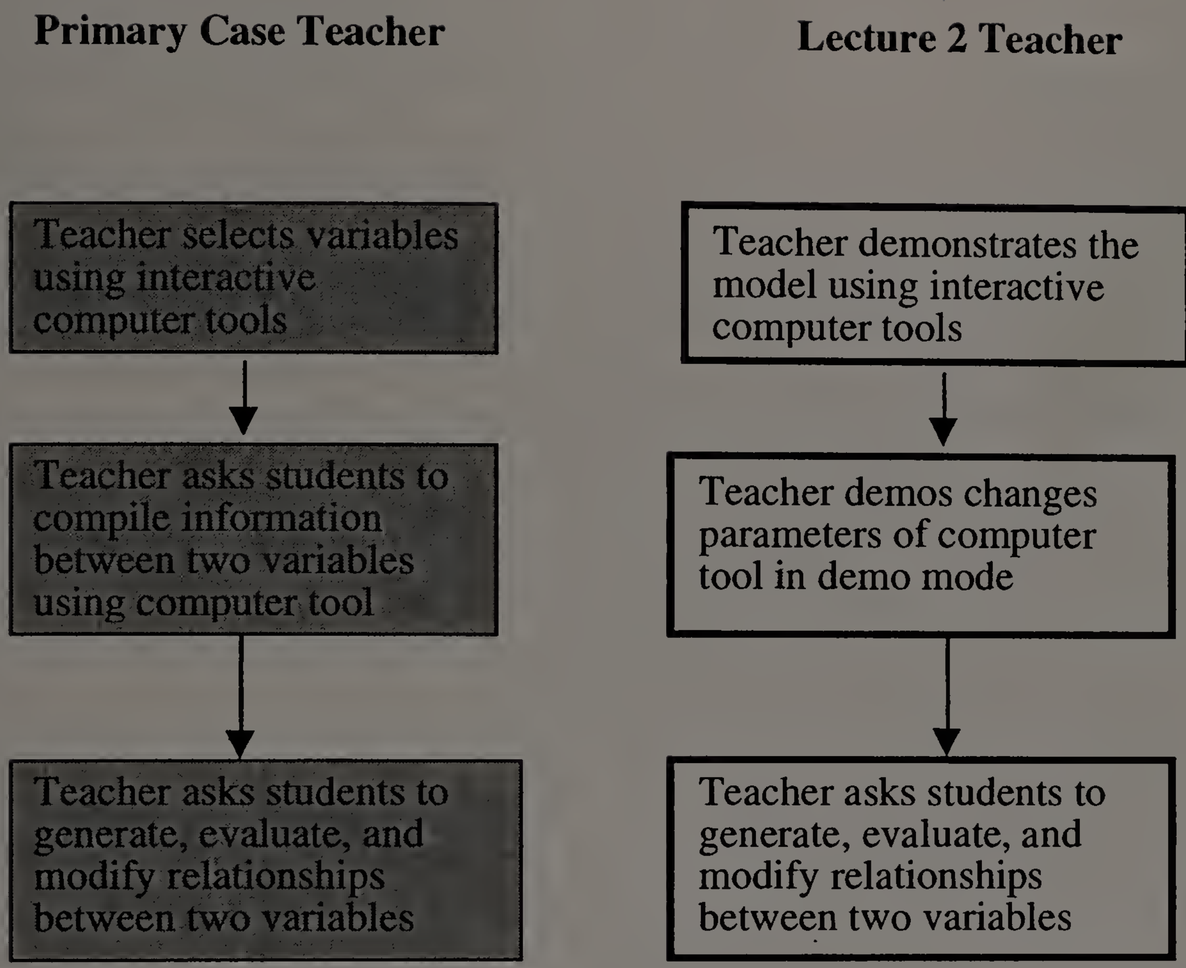


Figure 6. Contrasting the GD approach in the primary case and lecture 2.

Contrasting the primary case with Lecture 2.

Table 23. Contrasting pressure.

Primary case	Lecture 2
T Defines a gas. Guess how fast in miles/hour are molecules whizzing around? S 10000 mph? Background info S 1 mph? T introduces simulation of a Boltzmann distribution [BZD] for oxygen and shows the range of speeds, temperature scale, and selection of molecules. Variables They [the oxygen molecules] go at a range of speed, so some are going slow, some are going fast. And so it's very much like a plot of cars on a highway. So some cars are going like 90, very few of them are going 90, lots of them are going you know a bunch are going 80, most are going you know 60 or 70, very few are going 30 or 40 or whatever. So it's like if you were watching a highway for a long time. So that's what this is for gas molecules. What is going to happen if temperature increases? Compile information Generate relationship S Shifts to a higher velocity. S Runs the BZD simulation and points to the graph in the simulation. Why is it also getting shorter? (referring to the peak). S More are moving at the same speed? T No. S More collisions, so it is more chaotic so a wider range? T No, just a wider distribution because you have to have the same area underneath the curve. Let's compare different gases (using the BZD sim). What is the reason why He is different from O_2? Generate relationship S Size and weight. T What is the trend? S He is lighter T Therefore, moving?	T How do you figure out how much gas is in this room? S Measure T,P, volume. T We will try to come up with an understanding of T,V,P at the molecular level. Demo model Shows an animation of a container. T How would you figure out the volume of a container? Measure the size. What does temperature and pressure mean? Runs animation. What's happening? S Bouncing around. Hitting the sides. S They exert pressure on the walls. T How? Change parameters S Hit walls. S Change direction T There must be a force exerted on it! Is the pressure constant or changing? S T Changes depending on how many molecules hit the wall at any given time. S only so many molecules. T How many moving at the same speed? S No. T S Slow. T Hotter? S Fast. They all sped up. T All the same speed? S No. T They all sped up? S Sped up on average. T What do you have to do? S Add Energy. T Heat up. Where does the energy go? T Into gas molecules. S Increase speed. T Because velocity is related to kinetic energy. S The smaller the volume, the harder it is to measure how much there is? T Not necessarily. T What would I change to make pressure greater? S answer. T What are molecules doing if I increase the kinetic energy and why? S If they are moving faster.

Primary case	Lecture 2
S Faster. T Why? Because it is lighter is it moving faster? T relates mass and velocity. Call the KMT of gases. $KE=1/2mv^2$ proportional T. Why does the lighter element go faster? S Takes less energy to move something lighter further. T Keep picturing molecules; let's talk about an ideal gas. Provides definition. Think about pressure. Draws a container and says, these particles are going to collide with the container. Pressure is proportional to number of collisions with walls of the container. We are going to talk about volume, T, n. What will happen to the number of collisions if I double the number of moles? Evaluate S Goes up. T By a factor of 2. Give me a relation between pressure and moles. S P is directly proportional to number of moles. T Temperature increases? S Average KE increases which means the molecules are bouncing off the walls more often. Modify T What is the relationship? S Pressure is proportional to T. S As vol increases, pressure goes down. T P is inversely proportional to v. T Now we could put all of these together into one mathematical expression. T PV is directly proportional to? S PV is directly proportional nT T PV = nRT (introduces the gas constant).	T They hit the walls harder. S And it's harder for them to turn around. T Collisions. Generate relationship S Add more molecules. T Well more collisions changes the pressure. So changing the force of collisions or the number of collisions will change the pressure. T draws a linear volume vs. mass graph. T If I have very little mass, what happens? Runs gas laws simulation and increases the mass. What happens if I increase the amount of gas in order to keep pressure constant? The volume increases. T increases temp on simulation. S Volume. T Volume increases. Why? T provides an explanation.

Table 24. Contrasting electrostatic forces.

Primary case	Lecture 2
T Sometimes it takes 6 years to make a molecule! We can do experiments to manipulate matter. This is unique to chemistry. Our goal is to bring everything back to the structures of atoms. Atoms have three particles. We need to move from viewing electrons as a dot to a cloud of electron density. Viewing electrons as particles is useful for 1% of what chemists do. We will use simulations to get a gut feeling of the relationships in Chemistry. Go to Coulomb's law simulation. T shows the parts of the simulation. Play, observe, write down what you observe, come up with the rules. Who can tell me the relationship between distance and the electrostatic force? [using Coulomb's law simulations]. S As distance increases, the force gets smaller. Generate T force is inversely proportional to distance. Try to double the distance and see what happens. Evaluate S2 It's d^2 T Now look closely between the magnitude of charges and what the force is. S3 It changes in increments. T What do you see? S When we go from –1 to –2, the force doubles. T Does it double again from –2 to –3, from –1 to –3,look at the force values, go on and make changes to the simulation. T demonstrates and states it is going up in multiple of 1.4. T Therefore force is directly proportional to charge 1 times charge 2 over dsquared. The larger charges, the stronger the force. The larger the distance, the weaker the force. Electrostatic force is the most important force. Modify T Draws a cloud picture of ^{24}Mg and says what's wrong with this picture [model] based on Coulomb's Law? Evaluate S1 Why don't electrons pull into the protons? S2 Is the distance between the electron cloud and nucleus set?	T Historical overview to see about the scientific reasoning behind this. People knew that elements and compounds exist. Provides example of static electricity. Creates a table of subatomic particles with mass on the left hand column. Draws an electron cloud and places Coulomb's law simulation on the overhead. Demo model T What is the main force off attraction? S Gravity. T Another force is the electromagnetic force. Demoes Coulomb's law simulation. What do you want to look at first, distance, size, charge? S Distance. T increases distance. Does force get larger or smaller? S's Smaller. Change parameters T summarizes a conclusion. S The forces between two charged particles is stronger when closer. T writes this on the board. S Now increase the charge. T -1 to –2 How much did it change by (referring to force of attraction) What does this mean about F and charge? S Exponentially? T Try drawing this graph. Shows multiple different relationships on force vs. charge graph and takes a student poll. T If I increase the charge, the strength of the charge increases. So is it a or b line? S Should be a because it increases at the same rate. T by a factor of two. That's a linear relationship. Generate relationship Therefore, force is a linear function of the charge. T changes both charges to positive S No electrostatic forces? T Both +, what happens? Is the magnitude of the repulsive forces different? S They are the same. T What about this picture, what makes sense, what doesn't? Referring back to the electron cloud picture.

Primary case	Lecture 2
S1 We learned it as rings, remember? T What doesn't make sense? S6 Some electrons should be at different places like a p orbital. S7 Why don't electrons collapse into the nucleus? T Electrons are always trying to get closer to the nuclei. Always. S8 What is between the cloud and the nucleus? T Mostly a vacuum. Another glaring problem! S9 Why do all the protons stick together in the nucleus? T What holds the nucleus together? S10 Strong force. T The strong force operates only at close distances unlike electrostatic forces, what works at long distances, keeping protons together. [Shows a plot of stability vs. distance] Net forces cancel each other. T Writes nuclear stability on the board and Strong force of attractions plus the electrostatic force of repulsions gives the nuclear stability. ^{2}He has two protons and two neutrons and two electrons so we say that it has 4.00 atomic mass units but experimentally, He is 4.003. This difference in mass has been converted to energy. $E = mc^2$ and that is the net stability of the atom. What's more stable? 3 ^{4}He or 1 ^{12}C? [S do calculations] Modify [T asks for a vote] S11 ^{12}C because the lower the energy, the more stable. S12 3 ^{4}He because He is a noble gas so it would be more stable. T We are talking about nuclei. The greater the mass loss, the greater the stability. T [from an overhead], between you all, what element has the largest number [ie. Nuclear stability]? It turns out that Fe is the most stable. [T provides an equation for determining the most nuclear stable]. Why is it that when you get past Fe, it gets less stable? S14 Aren't these elements radioactive? S15 Well the mass loss increases as you get up to ^{56}Fe and that is greater stability.	S discussion ensues T asks students in a list form. What does not make sense? Evaluate S Why the protons and neutrons stick together? S Why don't the electrons and protons stick together? S Why not electrons and neutrons or light particles in the nucleus? T What does make sense? S Electrons repel, so they aren't clumped. S Protons and neutrons have the same mass, so maybe they are similar, that's why they start together (nucleons). T If I have two things that repel each other, but there are consistently stuck together, what's going on? S There's a different charge there. Modify T There is some other force "strong nuclear force" is short range. Only works with protons and neutrons and always attractive. Why don't electrons and protons stick together? Quantum mechanics. Higher PE away from the nucleus. Everything tries to get to a lower energy state but quantum mechanics says that at the atomic level, that doesn't hold so well. Electrons have to have at least some energy and that means they can't get all the way down to the nucleus.

Primary case	Lecture 2
and after ^{56}Fe, the less the mass loss, the less stable. Explain S19 As you put nuclei together, the strong force works. When the nucleus is too big, repulsions start having a greater effect than the strong force.	

Differences in computer use between lecture 2 and the primary case. The instructor in lecture 2 attempted to implement the GD approach with a single computer in a large lecture theater classroom setting with over 120 students. In order to modify the GD approach for use with a single computer in the large lecture theater setting, the lecture 2 instructor demonstrated the use of interactive computer tools. For example, in all three lessons observed, the Lecture 2 instructor began the lesson by displaying a model of a chemical phenomenon or a representation of lab results using the Chemland simulations on an overhead or a drawing on the blackboard. The instructor changed the parameters of the simulation and asked students what would happen if a variable in the simulation was increased or decreased. The chief difference between lecture 2 and the primary case's use of the computer was that the primary case teacher asked students to select variables using interactive computer tools in the electronic classroom and compile information between the two variables, whereas the lecture 2 instructor demonstrated the simulation and increased or decreased values as a whole class demonstration. Thus, in order to implement the GD approach in the large lecture theater, the lecture 2 instructor was observed using a single computer in demonstration mode to facilitate instruction. Instructor demonstration mode was a different use of the computer from the student interactive use of computers in the primary case.

The lecture 2 instructor was observed using the computers in demonstration mode in the lecture theater every classroom observation. The majority of Lecture 2 students that were surveyed (n=102; post CAT survey) confirmed that computer computer simulations were used to explain chemistry greater than 20 times in the lecture 2 class. The same frequency of computer use was selected by the majority students in the primary case who were also surveyed (n=21) on this item:

"Computer simulations were used to explain chemistry____________ in the class."

About once every two classes or greater than 20 times in total

About once every three classes or between 10 and 19 times in total

About once every six classes or between 5 and 9 times in total

About once a month or between 1 and 4 times in total

At no time

Thus, the instructor in Lecture 2 used computers in demonstration mode in the class. The use of the computer was observed regularly in the lecture 2 throughout the semester, and may have been used as often as in the primary case.

Differences in instruction between the primary case and lecture 2. Aside from the differences in the way the computer was used in the large lecture theater, it appeared that the central pattern of instruction by the lecture 2 instructor was similar to the primary case teacher. By examining tables 34 and 35, the primary case teacher and the lecture 2 instructor were both detected asking students to generate a relationship between two variables after the information was compiled. After generating the relationship, both teachers encouraged students to evaluate the relationship in light of discrepant information and modify the relationship to take this new information into account. Thus, instances of the lecture 2 instructor asking students to generate, evaluate and modify relationships (GEM), and construct explanations were detected in the lecture 2 class. These classroom observations were further supported by lecture 2 student survey results from the CAT post-survey that suggested that lecture 2 students were being asked to do activities associated with GEM cycles:

1. 64% of surveyed students in lecture 2 (n=104) were in agreement that, "There are more frequent opportunities to generate scientific ideas in this class than in most other classes".

2. 55% surveyed students in lecture 2 (n=103) were in agreement that, "There are more frequent opportunities for students to make and test predictions in this class than in most other classes".

3. 67% surveyed students in lecture 2 (n=103) agreed that, "I have been asked to construct explanations about scientific information or observations during class".

4. 52% of students surveyed in lecture 2 (n=103) agreed that, "I was frequently asked to analyze data from a graph or table in the class".

5. 58% of students surveyed in lecture 2 (n=103) agreed that, "I am asked to challenge or evaluate a scientific idea more often in this class than my other classes".

Thus, the majority of students in lecture 2 agreed that they were asked to generate and evaluate ideas in chemistry, a key component of the GEM cycle in the GD approach to instruction. It was generally observed that the lecture 2 instructor was able to implement the GEM cycle in the lecture 2 classroom.

Upon closer examination of instruction in lecture 2, however, some observable differences in the implementation of the GD approach appeared to emerge between the lecture 2 and the primary case. Namely, we observed that the lecture 2 instructor was implementing GEM cycle activities but not scaffolding them. Classroom observation notes revealed that the lecture 2 instructor did not incorporate the guidance strategies to that were associated with teacher activities in the primary case. Thus, using a demonstration computer, the lecture 2 instructor appeared to initiate GEM cycle activities like the primary case teacher but the specific guidance strategies that were observed in the primary case were noticeably absent in lecture 2.

4.9.6 Summary comparing instructional patterns

Using classroom observation notes and student CAT surveys as evidence, I have attempted to characterize instruction in the primary case. The classroom observation notes and CAT surveys uncovered a central pattern of instruction. The central pattern of instruction in the primary case was referred to as the guided discovery (GD) approach and was characterized by generate, evaluate, and modify or GEM cycles, other teacher guidance strategies, and the integration of Chemland interactive computer tools. Six teacher activities were identified that triggered GEM cycles, some of which included asking students to compile information from Chemland, asking students to find the trend in the information, and providing discrepant information. Associated with the teacher activities were fifteen other teacher guidance strategies, including using analogies, extreme cases, comparisons, incremental values, work back from the data, design a new test, what is wrong, why, think of an individual molecule, gather more information, see if this holds true, and test new variables. The teacher and the students worked with Chemland to select and constrain variables, produce data quickly, dynamically regenerate graphs, push values to the extreme, pause and proceed in increments, and visualize multiple, color coded representations. Thus, the GD approach to instruction consisted of teacher activities that triggered GEM cycles, specific guidance strategies to support GEM cycles, and the full integration of computer tools. The GD approach to instruction was sustained throughout the semester in the primary case.

In contrast, however, the lecture 1 instructor was observed implementing a linear pattern of instruction that was characterized as term introduction, demonstrations or examples; and modeling problem solving. This approach to instruction was observably different from the GD approach to instruction. Key GD approach teacher activities such as asking students to generate, evaluate, and modify relationships, make and test predictions, or analyze graphs were not observed in lecture 1. In this regard, the activities in the primary case could be considered distinctive compared with the more traditional approach to instruction that was represented by lecture 1.

In comparison to lecture 2, the lecture 2 instructor did attempt the GD approach in the lecture classroom with a single demonstration computer. Classroom observations revealed that the lecture 2 instructor appeared to initiate GEM cycle activities but did not appear to incorporate the specific guidance strategies that were observed in the GD approach to instruction in the primary case. The lecture 2 instructor modified the GD approach to instruction by working in demonstration mode with the computer and not incorporating the specific guidance strategies. Thus, in comparison to the lecture classes, the GD approach with the combination of GEM cycle activities, specific teacher guidance strategies and interactive computer tools in the primary case could have been considered a somewhat distinctive combination of teacher activities in the department.

4.10 Whole classroom student responses to GD instruction

The GD approach to instruction was designed to trigger a response from students. This section will focus on the general classroom responses to the GD approach using the classroom observation rubrics, focus group transcripts from the pilot study (Khan, 2001), and the CAT surveys to characterize this response. To place the instructional strategies and classroom interactions in the primary case into context, student responses to the GD approach to instruction in the primary case will be contrasted with the GD approach to instruction in the lecture 2 class.

4.10.1 Whole classroom student responses to GD instruction

Based on the classroom observation rubrics, the whole classroom was observed responding to instruction. The classroom observation rubric coded by method of interaction and by process. The methods of interaction were coded in the classroom observation rubric as follows:

Method:

Whole class/teacher interaction: 1. Prepared lecture 2. Lecture/discussion

3. Discussion 4. Hands on activity

Small Group activity: 5. Discussion 6. Hands on

Student presentation: 7. One or more

Individual activity: 8. Hands on 9. Thinking/writing/reflecting

Based on these codes for methods of interaction, student responses in the primary case were detected and are represented in Table 25.

Table 25. Methods of teacher-student interactions in the primary case.

<table>
<tr><th>Lesson Observed</th><th>2:30-2:45</th><th>2:45-3</th><th>3-3:15</th><th>3:15-3:30</th><th>3:30-3:45</th></tr>
<tr><td>1</td><td></td><td colspan="2">5</td><td>1</td><td>5</td></tr>
<tr><td>2</td><td>1</td><td>3</td><td colspan="3">2</td></tr>
<tr><td>3</td><td>5</td><td colspan="4">3</td></tr>
<tr><td>4</td><td colspan="5">3</td></tr>
<tr><td>5</td><td>5</td><td colspan="2">3</td><td colspan="2">2</td></tr>
<tr><td>6</td><td colspan="3">5</td><td colspan="2">2</td></tr>
<tr><td>7</td><td></td><td colspan="4">2</td></tr>
<tr><td>8</td><td colspan="3">4</td><td colspan="2">2</td></tr>
<tr><td>9</td><td>5</td><td>2</td><td>3</td><td>2</td><td>3</td></tr>
<tr><td>10</td><td>1</td><td colspan="2">2</td><td colspan="2">3</td></tr>
</table>

According to Table 25., students in the primary case responded to their teacher by participating in predominantly method 3, or whole class discussion with their teacher, followed by method 2, lecture discussion with their teacher, and method 5, small group discussion with their peers. Thus, students were observed responding to their teacher in three different modes: whole class discussions, lecture discussions, and small group discussions in the primary case as detected by the classroom observation rubric.

Student responses also corresponded with teacher directives and the phases of instruction in the GD approach, as exemplified in Table 26. Table 26 lists the phases of instruction in the GD approach, the major teacher activities associated with each phase of instruction and the mode of teacher-student interaction (whole class discussion, whole class lecture, or small group discussion). It is during these modes of teacher-student interaction that contiguous teacher-student sequences were observed.

Table 26. Contiguous teacher-student sequences in the primary case.

Instructional Sequence	Teacher Activity Structure	Contiguous Teacher-Student sequences
Background info	Provide content	Whole class lecture mode
Compilation of information and generation	Compile information using the interactive computer tools	Small group discussion mode
	The teacher asks students to find the trends	Small group discussion mode
	The teacher guides student generation of relationships	Whole class discussion mode
Evaluation	The teacher asked students to evaluate relationship in light of new information	Whole class discussion mode
Modification	The teacher guides the evaluation and modification of relationships	Whole class discussion mode

Contiguous teacher-student sequences in response to teacher instruction were detected in the primary case.

Discussion of student responses to the GD approach in the primary case. When background information was provided by the primary case teacher to the students, this activity was conducted as a lecture discussion (mode 1 in the classroom observation rubric). Students were observed responding to the material by asking the teacher questions and writing notes. According to the classroom observation notes, the next phase of instruction was generating relationships. In this phase, the teacher typically asked students to work in pairs or groups of 3 (mode 5 in the observation rubric) to compile information about the relationship between 2 variables. Students were observed responding to this activity by moving into small groups of 2-3 students, talking to each other in small groups, and clicking on the interactive computer tools. Addressing the whole class, the teacher would then ask student groups about the relationship they had generated after compiling information from the interactive computer tools. Students were observed responding to this teacher activity by raising their hands and answering with the relationships they had generated. In cases where a number of different relationships were generated by the small groups, the primary case teacher was observed giving students positive feedback, polling students on their choices and then discussing the merits and shortcomings of each hypothesis until one was selected as being the most viable. In cases where the primary case teacher wanted to construct a more complex relationship or students appeared to need additional guidance, the primary case teacher was observed scaffolding students ideas by asking the whole class questions. The evaluation and modification cycle typically lasted 15 minutes and was observed to occur in small group discussions around the computer, culminating in a whole class discussion on a modification to the relationship. Also, specific guidance strategies were observed in every phase of the GD approach normally as a whole class discussion between the teacher and students. Student responses to these activities were continuously recorded throughout the semester. Thus, students in the primary case were observed responding to instruction in a contiguous sequence of teacher-student interactions that were detected by the classroom observation rubric.

Small group discussion in the primary case. In response to the primary case teacher asking students to compile information in small groups with the interactive computer tools, and the primary case teacher asking students to find the trends in small groups, students were observed moving into small groups in the primary case. The benefits of this mode of interaction were explored in a focus group of primary case students. In a previous pilot study (Khan, 2001) of the primary case, two focus groups of primary case students (n=4; n=3) offered this description of small group discussion in the primary case: "When we sit in groups and we talk about it, we'll question each other: 'Ok, wait a second, explain that again'. And they'll explain it again, but they might even themselves find something that's wrong with their thinking, or one of us will point it out. Just by talking with each other you can find the little mistakes-and help each other switch them and totally help each other explain the concept. And understand it. I think it helps me a lot." Another focus group student from the primary case described group dialogue as: "If someone's saying, 'I can't figure out where you go from there' and you can [say], 'if you do that first, then maybe you could do this'. [W]hen you're thinking about it together in the group-- making up rules, other people spark other people." These statements suggested that peer discussion gave students in the primary case the opportunity to question each other and provide alternative explanations. By participating in group discussion, students could uncover "what's wrong with their thinking" or misconceptions, and "spark" each other to generate new ideas. The majority of students surveyed in the primary case (CAT pre-survey; n=33) agreed with the statement that, "Peer discussion is valuable for my understanding of science topics". Thus, in response to two teacher activities in the GD approach, students in the primary case were observed moving into small groups. According to a focus group of students from the primary case (Khan, 2001), small group discussion was considered to be a valuable way for students to respond to each others' ideas.

4.10.2 Whole classroom student responses to GD instruction in Lecture 2

The lecture 2 instructor attempted the GD approach to instruction in a large lecture theater with one demonstration computer. During the GD approach to instruction in lecture 2, the most common student response to the instructor was observed in mode 2, or lecture discussion. Lecture discussion was usually an instructor question to the whole class with individual student response, or a demonstration (simulated or with real materials) to the whole class with an individual student response. According to the classroom observation rubrics, the whole class question and individual student response interaction (lecture discussion mode 2) in the lecture 2 class remained consistent throughout the lesson, whether the lecture 2 instructor was presenting a graph or picture, conducting a demonstration, or asking students to generate a relationship. Students were not observed working in small groups in the lecture 2 class. Thus, lecture discussion remained the consistent method of teacher-student interaction without use of small group discussion mode throughout all of the lessons observed in lecture 2.

A contiguous sequence of teacher-student interaction was observed during lecture discussion in lecture 2. Although a contiguous teacher-student interaction was observed during lecture discussion in lecture 2, the frequency of student responses to the GD approach to instruction in lecture 2 appeared to occur less often than student responses to GD instruction in the primary case. This finding will be explored further using the classroom observation rubrics and survey statements in the next section.

4.10.3 Summary of whole classroom student responses to GD instruction

The GD approach to instruction was implemented in two classes that were observed: the primary case and lecture 2. Contiguous Teacher-Student sequences were observed in both cases. The predominant mode of teacher-student interaction was whole class discussion with the teacher in the primary case, compared with lecture discussion in lecture 2. Another difference between the modes of interaction in the primary case and lecture 2 was that small group discussion was not observed in the lecture 2 but was observed in the primary case. According to students from the primary case who participated in a focus group, the benefits of participating in small group discussion were that students could uncover "what's wrong with their thinking" or misconceptions, and "spark" each other to generate new ideas. Thus, a contiguous teacher-student sequence was observed in a lecture discussion mode in lecture 2, whereas a contiguous teacher-student sequence was observed in whole class discussion mode and small group discussion mode in the primary case.

Even though a contiguous teacher-student response to the GD approach was observed in the primary case and in lecture 2, the frequency of student responses to the GD approach to instruction in lecture 2 appeared to be lower than the frequency of student responses to the GD approach to instruction in the primary case. This observation will be explored even further in the next section on process skills with a closer analysis of the classroom observation rubrics in both classes.

4.11 Process skills

The classroom observation rubrics were designed to record frequencies of classroom activities according to categories of processes associated with scientific inquiry. The classroom activities were coded by method of instruction, time segments, and whether they originated from the instructor (I) or the student (S). There were 6 major categories of processes: generating ideas, gathering information, critiquing results or conclusions, primary literature skills, verbal skills, quantitative skills, and content. By recording the frequency of process behaviors in the classroom, a profile of teacher actions and student responses emerged. The next section reports data from the classroom observation rubrics and follows with an analyses of the results and discussion of the findings.

4.11.1 Data in the primary case

The classroom observation rubrics indicated the frequencies of observable teacher activities to promote, or student evidence of, processes during classroom interactions. For the primary case, the raw numbers of hand-counted instances over 10 lessons in total of the primary case were tabulated in Table 27. An analysis and discussion of the data in Table 27 follows the table.

Table 27. Instances of observable processes in the primary case.

Instructor actions to promote or model = I Student evidence = S		Time: Method: I	S
Generating Ideas	Questions for or as a result of inquiry	7	
	Predictions (simple hypotheses) or rules concerning simple relationships between variables	32	25
	Experimental Designs or Tests		3
	Explanations or Conceptual Models (causal or mechanistic explanations – why or because. Could be done before or after testing, reflection, evaluation, or problem-solving)	38	37
Gathering Information	Data during experimentation or observation		
	Selecting and/or organizing relevant data or information from other sources (emphasis on need for selection, not simple compilation)		
Critiquing Results or Conclusions	Evaluating logical, empirical, or conceptual consistency (may include consideration of implications; may include a look at quality of evidence for a conceptual model)	19	18
	Critiquing experimental design, weighing experimental evidence, justifying ideas in light of such evidence.		1
	Comparing alternative theories or theoretical frameworks	3	
Primary literature skills	Finding, reading and organizing primary literature; discussing use of primary literature and relevance to inquiry	1	
Verbal skills	Communication in science through writing or presentations		
Quantitative skills	Analyzing data: Organizing, representing, and analyzing data; use of various representations and analysis tools (Excel or stat. package). Statistical data analysis		

Instructor actions to promote or model = I Student evidence = S		Time: Method: I	S
	Quantitative problem-solving and modeling (discusses, demonstrates, or refers to quantitative problem solving or using numerical models in science)	24	17
Content	Field-specific bodies of knowledge; gives content information in any form	38	12
	Field-specific cognitive skills (thinking/problem-solving skills specific to domain, e.g. Punnet square, free-body diagrams, medical procedures)	3	
	Field-specific lab skills	1	1

4.11.2 Results of teacher activities in the primary case

The data in Table 27 was analyzed, and the results for teacher activities were reported in the list below.

1. Teacher actions to promote or model the generation of questions for or as a result of inquiry plus the generation of simple relationships or rules between variables represented approximately four instances of the teacher acting to promote or model the generation of ideas per class (39/10) in the primary case.

2. Generating experimental designs or tests, gathering experimental data, or critiquing experimental designs were not observed being promoted or modeled by the teacher in the primary case.

3. There was an almost equivalent attempt by the teacher actions to promote or model generating relationships as there was teacher actions to promote or model explanations or give content information (39 teacher actions to promote or model

inquiry questions and generate relationships; 38 teacher actions to promote or model explaining ideas, and 38 teacher actions to promote or model giving field specific content information in any form in a total of 10 classroom observations) in the primary case.

4. Teacher actions to promote generating ideas occurred more frequently (32 instances in total) than teacher actions to promote or model the evaluation of the consistency of the relationship (19 instances in total) in the primary case.

5. Field specific bodies of knowledge were provided by the teacher in 38 instances compared with 39 instances of teacher actions to promote the generation of testable questions or hypothetical relationships in the primary case.

4.11.3 Results of student processes in the primary case

The data in Table 27 was analyzed, and the results for student processes were continued in the list below.

6. No instances of students generating inquiry questions was observed in the primary case.

7. The highest number of observable processes in each class were students generating relationships between two variables (25 instances observed in total) and students generating explanations (37 instances observed in total) in the primary case.

8. Students relatively rarely generated a question or an idea about experimental designs or tests in the primary case.

9. Students were observed evaluating the consistency of their initial relationships close to two times in every class in the primary case.

10. Students were not observed comparing theoretical frameworks, reading primary literature, communicating in science through presentations, or doing statistical analyses in the primary case.

11. Students were observed working with quantitative models close to two times in every class in the primary case.

12. Students were observed giving content information in any form only in 12 instances in 10 classes in total in the primary case.

13. Field specific cognitive skills and lab skills were not observed or observed rarely in the classroom in the primary case.

4.11.4 Analyses of teacher activities and student processes in the primary case

Seven main findings emerged from an analysis of teacher activities and student processes in the primary case.

1. There were observable instances recorded in the classroom observation rubric of teacher activities to promote or model processes and student evidence of the very same processes in the following six categories: generating predictions (simple hypotheses) or rules concerning simple relationships between variables; generating explanations or conceptual models (causal or mechanistic explanations – why or

because; evaluating logical, empirical, or conceptual consistency; quantitative problem-solving and modeling (using numerical models in science); field-specific bodies of knowledge, and field-specific lab skills. This evidence further supported the whole classroom observation that there appeared to be contiguous teacher-student responses in the primary case during instruction.

2. Teacher actions to promote or model generating ideas occurred more frequently (32 instances in total) than teacher actions to promote or model the evaluation of the consistency of the relationship (19 instances in total) in the primary case. A relatively higher number of instances of generating ideas compared with evaluating ideas may have been detected because the modification of relationships was also coded as the generation of ideas.

3. Field specific bodies of knowledge were provided by the teacher in 38 instances compared with 39 instances of teacher actions to promote the generation of testable questions or hypothetical relationships in the primary case. This result suggests that field specific content information was being delivered in the primary case with the same frequency as teacher activities to promote generating questions or relationships in chemistry.

4. Observable instances of student responses that were generating relationships between variables, generating explanations or conceptual models, evaluating the logical, empirical, or conceptual consistency of the relationships, quantitative problem-solving and modeling indicated that students were engaged with these processes during instruction in the primary case. These activities represent some of the fundamental processes that have been commonly associated with inquiry in science.

5. There were no observations of students generating their own questions for inquiry in the primary case, but there was evidence for the teacher generating questions for inquiry, suggesting that in the lessons we observed, inquiry was directed initially by the teacher in the primary case.

6. There were no observations of students gathering and organizing data during experimentation or critiquing experimental design or evidence in the primary case. Experimentation was not a part of the GD approach to instruction or teacher guidance strategies. Rather, experimental activities were relegated to the lab portion of the course. Labs were associated with all introductory chemistry courses.

7. There was no evidence of students comparing theoretical frameworks, reading primary literature, communicating in science with presentations, or conducting statistical analyses of data in the primary case, suggesting that some of the processes associated with inquiry were not observed in the primary case.

Thus, the classroom observation rubrics detected that students respond to teacher activities in the primary case, and that these responses seemed to indicate that students in the primary case were engaged with several of the fundamental processes commonly associated with scientific inquiry throughout the semester.

4.11.5 Comparing data from the primary case with the lecture classes

In order to compare the teacher activities to promote or model processes and student evidence of processes between the primary case and the lecture classes, a ratio of instances of activities among the primary case, lecture 2, and lecture 1 was calculated. The ratios represented the relative proportion of observable instances of activities per lesson unit time period rounded to the nearest 0.5. Highlights of several of the ratios are included in Table 28. A discussion of the ratios and the implications follows Table 28.

Table 28. Ratios of instances of process activities per time period.

Ratios of activities observed per time period	Primary case	Lecture 2	Lecture 1
Teacher acts to promote or model questions for or as a result of inquiry	2	1	0
Student evidence of questions for or as a result of inquiry	0	0	0
Teacher acts to promote or model generating ideas in chemistry	2	2	1
Student evidence of generating ideas in chemistry	3	2	1
Teacher acts to promote or model generation of explanations or conceptual models	1	1	1
Student evidence of constructing explanations or conceptual models	4	2.5	1
Teacher acts to promote or model evaluating logical, empirical, or conceptual consistency of results or conclusions	1	1	0
Student evidence of evaluating logical, empirical, or conceptual consistency of results or conclusions	1	1	0
Teacher acts to promote or model quantitative problem solving	2	1	0
Student evidence of quantitative problem solving	4	1	0

4.11.6 Analysis of process comparisons

Based on Table 28 highlights and process ratios that were not included in the table, the teacher and student ratios per category in all three classes are discussed below. In general, the teacher ratio is discussed first and then the student ratio. CAT survey data and transcript examples from the observation notes of the primary case and lecture classes are also included. Implications of the results are also suggested.

Generating inquiry questions.

1. On average, teacher actions to promote or model questions for or as a result of inquiry were observed double fold more often in the primary case than Lecture 2 and zero times in the Lecture 1 class. There was no evidence of student generation of questions that launched inquiry in any of the three classes observed and that suggested that inquiry was not student-directed in any of the three classes.

> Eg. Lesson 1 from the primary case.
> T How would you determine how many golf balls would fit in this room?

Generating ideas about chemistry.

2. The teacher acted to promote or model generating ideas in the primary case an equivalent number of instances on average per unit time as lecture 2, and twice as often as lecture 1. Compared to lecture 1, students from the primary case generated ideas about chemistry 3 fold more often than students in lecture 1. Students from lecture 2 generated ideas about chemistry double fold more often than students in lecture 1.

> Eg. Lesson 3 from the primary case.
> T presents an isoelectronic series of O^{2-}, F-, Ne, Na^{+} Mg^{2+} and says which do you expect to be the largest?
> S12 O^{2-} because they have the same number of electrons with a different nuclear charge.

> Eg. Lesson from the primary case.
> T Take a look at a table [on the overhead] for C-F, C-I, etc. Shows kJ/mol of all the bond energies of different atoms.

S14 The closer together, the stronger the attraction therefore, it's harder to break [referring to C-F vs. C-I].
T Why?
S14 Coulomb's Law?
T r^2 doesn't work here. C and F are bonded at lower energy levels.
S15 So then it's harder to pull electrons when they are closer to the nucleus.

Making predictions.

3. Students surveyed in lecture 2 did not significantly differ on the CAT post-survey statement, "There were more frequent opportunities for students to make and test predictions in this class than in most other classes" from students surveyed in the primary case. This survey result was support by a 1:1 ratio of classroom observations of instances of students' making predictions or rules concerning simple relationships between variables between the primary case students and the lecture 2 students from the classroom observation rubric.

Constructing explanations.

4. It was detected that on average, the primary case teacher acted to promote or model explanations in chemistry in an approximately equivalent ratio to the lecture classes. It was detected, however, that students constructed explanations over 4x more often in the primary case than in Lecture 1 and almost twice as often than the Lecture 2 classes.

Eg. Lesson in the primary case.
T Go to Chemland's orbital energies. What happens to the energies as you go right across a period and all the way down?
S7 The orbital energies get lower as you go across.
T What happens as you go down?
S7 The orbital's energy goes down?
T But the energies are going up! Why is that?
[S discussion in groups ensues]
T Why? Think about the charge to charge interaction with the nucleus?
S8 As you go across the table [periodic table], aren't the orbitals getting bigger, that is, they have more electrons?
T Is the radius going up? Think of effective charge.
S9 Well, there may be electron shielding as you further across [the periodic table]. There are more protons too and that leads to a higher Zeff . So there are more protons, the electrons are held more tightly.

Evaluating relationships in chemistry.

5. The primary case teacher acted to promote or model evaluating logical, empirical, or conceptual consistency of relationships in chemistry in a relatively equivalent proportion to the lecture 2 class teacher. There was no evidence of the lecture 1 instructor asking students to evaluate relationships in chemistry.

There was a significant difference between the lecture 2 and lecture 1 class on the CAT survey statement that, "I am asked to challenge or evaluate a scientific idea more often in this class than my other classes" with more surveyed students agreeing to this statement in the lecture 2 class than in the lecture 1 class ($p=0.01$). There was no significant difference on this statement between surveyed students from the primary case and the lecture 2 class.

Eg. Lesson in the primary case.
T Draws a cloud picture of ^{24}Mg and says what's wrong with this picture [model] based on Coulomb's Law?
<u>S1 Why don't electrons pull into the protons?</u>
S2 Is the distance between the electron cloud and nucleus set?
S1 We learned it as rings, remember?
T What doesn't make sense?
S6 Some electrons should be at different places like a p orbital.
<u>S7 Why don't electrons collapse into the nucleus?</u>
T Electrons are always trying to get closer to the nuclei. Always.
S8 What is between the cloud and the nucleus?
T Mostly a vacuum. Another glaring problem!
<u>S9 Why do all the protons stick together in the nucleus?</u>
T What holds the nucleus together?
S10 Strong force.
T The strong force operates only at close distances unlike electrostatic forces, that works at long distances, keeping protons together.

There was an equivalent ratio of student evidence of evaluating logical, empirical, or conceptual consistency of relationships in chemistry between the primary case students and the lecture 2 students. Student evidence of evaluation was in the same proportion as teacher actions to promote or model evaluation of relationships in chemistry in the primary case and lecture 2. Evaluating an idea in chemistry in light of discrepant information was not observed from the students lecture 1.

Quantitative problem solving.

6. Promoting or modeling quantitative problem solving by the teacher was observed 2x more often in the primary case than in Lecture 2's class, and this activity was not observed in Lecture 1's class. On average, students doing quantitative problem solving was observed 4x more often in the primary case's class than the Lecture 2 class, and it was not observed in the Lecture 1 class for the same time period. We observed the primary case students generating parts of quantitative formulas to do calculations [entropy, force of attraction, heat capacity] or evaluating graphs to determine quantitative relationships for the gas laws.

Eg. Lesson from the primary case.
T Go to Coulomb's law simulation. T shows the parts of the simulation. Play, observe, write down what you observe, come up with the rules. Who can tell me the relationship between distance and the electrostatic force? [using Coulomb's law simulations].
S As distance increases, the force gets smaller.
T Force is inversely proportional to distance. Try to double the distance and see what happens.

S2 It's $d^{2.}$
T Now look closely between the magnitude of charges and what the force is.
S3 It changes in increments.
T What do you see?
S When we go from –1 to –2, the force doubles.
T Does it double again from –2 to –3, from –1 to –3? Look at the force values, go on and make changes to the simulation. T demonstrates and states it is going up in multiple of 1.4.
T Therefore force is directly proportional to charge 1 times charge 2 over dsquared. The larger charges, the stronger the force. The larger the distance, the weaker the force. Electrostatic force is the most important force.

Experimental designs or tests.

7. Teacher activities designed to help students generate ideas about experimental designs or tests in chemistry by the teacher was evident only once and that was in lecture 1. Student evidence of generating ideas about experimental designs or tests in chemistry was evident only once in the primary case.

> Eg. Lesson 7.
> T What is the experimental evidence to measure the existence of resonance structures in benzene?
> S8 Bond length.
> T Are the length of bonds the same? Yes they are.
> S7 How do you measure bond length?
> T discusses X ray crystallography in experiments to determine bond length.

In all three classes, it may have been that these processes were relegated to the labs.

Gathering information during experimentation.

8. Gathering information during experimentation or from primary literature was not evident during class in any of the classroom observations from any class. Compiling information from computer simulations was not considered gathering raw data, and therefore, was not categorized as gathering information. Demonstrations were performed in the lecture 1 class, but students did not gather empirical data from the demonstrations either.

Critiquing experimental design.

9. Critiquing experimental design was observed in only one instance, and that was in the primary case from a student question.

Comparing alternative theories.

10. Comparing alternative theories or theoretical frameworks by the teacher happened in higher proportion in Lecture 2's class compared with the primary case, but was not observed in Lecture 1. One implication of this finding is that comparing alternative

theories did not appear to be a part of the the more traditional approach to classroom instruction as observed in Lecture 1. Generally, students were not observed comparing alternative theories in any of the three classes.

> Eg. Lesson 2 from the primary case.
> T Move from viewing electron as a dot to a cloud of electron density. <u>Viewing electrons as particles is useful for 1 % of what chemists do.</u>
>
> Eg. Lesson 3 from the primary case.
> S4 What determines electron spin?
> T Quantum mechanics theory. We say spin because electrons have magnetic properties and they act like they are spinning, but it is just a theory based on magnetic moment that we observe, so we think of it as a spin. This is not a game chemists made up.
> S5 Is an electron spin always static or does it change spin as it leaves the same shell?
>
> Eg. Lesson 4 from the primary case.
> T Valence Bond Theory (VBT) is very easy but limited to p block elements; Molecular Orbital Theory (MOT), on the other hand, is very difficult but it can explain vibration, absorption, light shining, hemoglobin. As chemists, we say MOT is the right way but it takes a long time so we may use VBT in professional journal articles and it's appropriate.

<u>Primary literature.</u>

11. Using primary literature was generally not observed in any of the classes by the teacher or the students; however, half of one lesson observed in the primary case was dedicated to using a protein database that scientists use to collect the most current information on new proteins. On occasion, issues about writing in professional journals were raised in the primary case. In all three classes, it appeared this process was not a part of the approach to classroom instruction.

<u>Communication in science through writing or presentations.</u>

12. Communication in science through writing or presentations was generally not observed in any of the classes by the teachers or the students. In one instance, however, the teacher for the primary case asked students to evaluate the presidential candidates

for an upcoming election on their policies concerning the environment or science. Students returned short, written essays on this topic. In all three classes, it appeared this process was not a part of the approach to classroom instruction.

Statistics.

13. Employing statistics was not observed in any of the classrooms by the teachers or the students. In all three classes, it appeared this process was not a part of the approach to classroom instruction.

Cognitive and lab skills.

14. Field specific cognitive skills were not generally detected in the lecture 1 class but were detected in singular instances by the teacher in Lecture 2 and the primary case.

> Eg. Lesson 1.
> S If we can't look inside [a black box] then how do you probe?
> T answers: In chemistry, we stick things in magnets, shine light on it, weigh things.

15. Field specific lab skills were detected in singular instances in Lecture 1, Lecture 2 and the primary case during the classroom observations.

> Eg. Lesson from Lecture 1.
> T How much energy is in my teaspoon of sugar? Where is it telling Energy?
> S Calories.
> T A calorimeter is used to measure the amount of energy in a substance.
> T Sparkly combustion demo of potassium chlorate with sugar. Writes combustion reaction of Mg. How can I measure Energy?
> S Weigh before and after combustion.
> T No, MgO weighs more.
> S Close system, heat water.
> T Heat given off by reaction=heat absorbed by the water.

4.11.7 Discussion of process comparisons

According to the classroom observation notes, the instructor in lecture 1 did not appear to design an approach to instruction that addressed the fundamental processes of science, so perhaps it was not surprising that student engagement in process skills was not detected by the classroom observation instrument in this class. Thus, lecture 1 had the least observable teacher activities or student evidence of process skills compared with teacher activities or student evidence of process skills in lecture 2 or the primary case. Compared to the other methods of instruction that were observed, Lecture 1 implemented a more traditional approach to instruction in introductory chemistry.

Both the the primary case and lecture 2 class implemented the GD approach to instruction, an approach to instruction that appeared to engage students in several of the fundamental processes in science according to classroom observation notes and the classroom observation rubric. The GD approach to instruction contained teacher activities that were observed triggering processes in both classrooms; however, when the frequencies of teacher activities to promote these processes and student engagement with these processes were compared using the classroom observation rubric, it appeared that student engagement with these processes in lecture 2 was less than student engagement with these processes in the primary case. The next section attempts to explain why students in lecture 2 were less engaged in processes than students in the primary case. Eight possible conjectures were generated below. Each conjecture was discussed until a viable hypotheses emerged. The best explanation is suggested in the discussion section following the eight hypotheses.

Demonstration computer.

Hypothesis 1. Students in lecture 2 were less engaged in processes than students in the primary case because the GD approach was modified in lecture 2 to be implemented with a demonstration computer. Demonstration mode was inherently less engaging for students than being in an interactive mode with the computer as in the electronic classroom of the primary case. Because the demonstration mode was less engaging for students in lecture 2 than an interactive mode, it reduced their participation in classroom wide activities.

We did observe that students were not able to interact with the computer themselves in lecture 2 as they were in the primary case. Thus, it may be plausible that computer demonstration mode in lecture 2 contributed to a lower level of student engagement in lecture 2's GD approach because working in demonstration mode is less interactive and less engaging than working with your own computer.

Honors students are more confident than non-honors students and primary case students are more confident than lecture 2 students.

Hypothesis 2. Students in lecture 2 were less engaged in processes than students in the primary case because there was a lower proportion of honors students in lecture 2 (14 honors/ 122 students total) than in the primary case (9 honors/33 students total), and honors students, because of their background and prior success in chemistry, are a group that is more confident and more willing to engage in scientific inquiry and discussions about chemistry than their non-honors peers, resulting in a higher number of observable instances of student engagement with processes in the primary case classroom.

Within the primary case and within the lecture 2 class, however, there were no significant differences on the CAT pre-survey between honors and non-honors students on their responses to survey items on interest in chemistry, persistence, anxiety about computer use, abilities, perceptions of prior science instruction and confidence. Thus, according the CAT pre-survey, students entering the primary case or students entering the lecture 2 class reported similar confidence levels regardless of whether they were honors or non-honors students within the class.

In addition, being an honors or non-honors student did not appear to make a difference in the CAT survey within each class, and neither did being enrolled in the primary case or the lecture 2 class. There were no significant differences between surveyed students in the primary case and surveyed students in lecture 2 on the statement that, "I am confident about my ability to solve chemistry problems" on the CAT pre-survey and the CAT post-survey. Thus, differences in levels of confidence did not appear to exist between honors and non-honors students within the primary case and lecture 2, or between the students in the primary case and lecture 2, suggesting that it was unlikely that differences in confidence about engaging in the material produced differences in students' level of engagement.

Student interest in chemistry as a subject.

Hypothesis 3. Students in lecture 2 were less engaged in processes than students in the primary case because students in lecture 2 were less interested in chemistry than students in the primary case. Students who are less interested in chemistry are less likely to participate in chemistry activities within the classroom, resulting in a lower number of instances of student engagement with processes in chemistry being detected by the classroom observation instrument.

There was a significant difference between the primary case and lecture 2 on the CAT pre-survey item (n=33, n=122) "Chemistry is one of the more interesting sciences", with significantly more students agreeing with this statement in the primary case than in lecture 2. This difference between the primary case and the lecture 2 class remained significant throughout the course. Thus, it may be possible that a lower level of interest in chemistry reported by students in lecture 2 contributed to their lower level of engagement in processes about chemistry compared with students in the primary case.

<u>Large lecture theater setting.</u>

Hypothesis 4. Students in lecture 2 were less engaged in processes than students in the primary case because students in lecture 2 were more reluctant to participate within the physical setting of a large lecture theater with over 120 students. This large lecture theater setting was intimidating for some students in lecture 2, reducing their participation in chemistry activities in class that they may have otherwise participated in if the class size had been smaller or they worked in small groups.

Small group discussion was not observed in lecture 2 according to classroom observation notes. Small group discussion may have been a method for reducing students reluctance to participate in whole class activities, especially if their ideas were first discussed within a small group.

Learning at a faster rate.

Hypothesis 5. Students in lecture 2 were less engaged in processes than students in the primary case because students in the primary case were learning at a faster rate than students in lecture 2, increasing the rate of their participation in processes throughout the course of one semester in the primary case beyond the rate of participation in processes of students in lecture 2.

When a sample of classroom observation rubrics at the beginning of the semester were compared with a sample of classroom observation rubrics at the end of the semester within the primary case, evidence of teacher activities and student engagement in the processes remained consistent. That is, there was not an appreciable difference between the frequency of teacher activities or student responses that were observed between the beginning to the end of the primary case. This result suggested that teacher scaffolding was not faded and that student responses to instruction were maintained at a consistent rate. Although there was a smaller number of classroom lessons oberved in lecture 2, it also appeared that there were no significant leaps detected in teacher activities or student engagement with processes between the beginning and the end of instruction in the lecture 2 class. Thus, it was difficult to assess whether students were learning at a faster rate in the primary case compared with students in lecture 2 since it appeared from the classroom observation rubrics that the teachers were not fading scaffolding in the primary case and student responses remained consistent from the beginning to the end of class instruction; however, differences in rates of learning may represent a plausible factor for the difference in student engagement with processes between the two classes. Further investigation would be necessary to confirm this hypothesis.

Lecture 2 teacher answering own questions.

Hypothesis 6. Students in lecture 2 were less engaged in processes than students in the primary case because the instructor in lecture 2 was answering his own questions. An instructor asking and answering his own question reduces the number of potential instances of student participation that can be detected by the classroom observation rubric.

Evidence of the lecture 2 instructor asking and answering his own questions compared is reported below:

Tabulation of the number of teacher questions that were asked and answered by the teachers. All of the questions and answers in each lesson were hand counted twice for the primary case and the lecture 2 and lecture 1 classes. The questions were grouped into questions that originated from the teacher or the student, and answers that were responded to by the teacher or the student. All questions recorded in the classroom observation notes were included in the data set except for administrative questions. Administrative questions were questions that were about homework assignments and due dates.

An average of the number of counts per lesson was tabulated. These averages allowed us to compare the frequency and types of questions that the primary case teacher asked during instruction, with the frequency and types of questions that the lecture instructors asked during instruction. The comparisons are tabulated below in Table 29.

Table 29. Counts of average number of question/answers per lesson.

Averages per lesson*	Teacher answers			Student answers		
	Primary Case	Lecture 1	Lecture 2	Primary Case	Lecture 1	Lecture 2
Teacher questions	1	4	8	16	21	12
Student questions	3	7	5	0.3	0.3	0

* Note: lessons are not equivalent in time. The lesson period was 50' in the lecture classes and 75' in the primary case.

I counted the teacher asking and answering their own questions on average 8 instances per lesson in lecture 2 and 1 instance per lesson in the primary case. Thus, the lecture 2 class instructor asked and answered his own questions an average of 8x more often per lesson than the primary case teacher.

Short-circuiting generating relationships. The classroom observations seemed to suggest that the questions that the lecture 2 instructor was asking and answering himself included asking and answering questions that were associated with the GD approach to instruction. For example, for the process activity of generating relationships between two variables, in the primary case, the teacher asked students to find the trends in the data and generate a relationship between 2 variables. Asking students to generate a relationship triggered a student response where students were observed generating relationships in the primary case. For example, the primary case teacher asked:

T What will happen to number of collisions if I double the number of moles?
S Goes up.
T By a factor of 2. Give me a relation between pressure and moles
S P is directly proportional to number of moles.
T Temperature increases?
S Average KE increases which means the molecules are bouncing off the walls more often.
T What is the relationship?
S Pressure is proportional to T.
S As vol increases, pressure goes down
T P is inversely proportional to v.
T Now we could put all of these together into one mathematical expression.
T PV is directly proportional to?
S PV is directly proportional nT.

T PV = nRT (introduces the gas constant)

This student response was recorded in the classroom observation rubric as evidence of student engagement with generating relationships in the primary case. In lecture 2, however, the lecture 2 instructor asked students to generate a relationship, but I observed him generate the relationship himself. For example, for the same topic in lecture 2, the lecture 2 instructor appeared to generate the relationships for the students:

> S Add more molecules?
> T Well, more collisions changes the pressure. So changing the force of collisions or the number of collisions will change the pressure. T draws a linear volume vs. mass graph.
> <u>T If I have very little mass, what happens? [Runs gas laws simulation and increases the mass]. What happens if I increase the amount of gas in order to keep pressure constant? The volume increases.</u>

Thus, it may not be surprising that students who were surveyed in the lecture 2 class did not agree that they were asked to generate ideas by their teacher as often as students who were surveyed from the primary case:

> Students in the primary case reported that there were more frequent opportunities to generate scientific ideas in this class than in most other classes significantly more often than students surveyed in the lecture 2 class (p=0.00). There were no significant differences on this statement between lecture 1 and 2 classes.

The classroom observation rubric also detected a higher average number of instances that primary case students were observed generating ideas about chemistry (average of 4 per lesson unit time) compared with the average number of instances lecture 2 students were observed generating ideas about chemistry (average of 3 per lesson unit time) in the lecture 2 class.

A lower level of student engagement with generating ideas in chemistry was detected in the lecture 2 class compared with the primary case, and this was despite an approximately equivalent ratio of teacher activities in lecture 2 that were detected to promote or model generating ideas in chemistry to teacher activities in the primary case that were detected to promote or model generating ideas in chemistry[9]. This finding may support the hypothesis that the lecture 2 instructor was asking and answering his own process questions thereby short-circuiting students' generation of ideas in chemistry.

Short-circuiting explanatory model construction.

Even though there was an approximately equivalent ratio of teacher activities detected for generating explanatory models[10] between the primary case teacher and the lecture 2 teacher , a lower level of student engagement with generating explanatory models per lesson unit time was detected in lecture 2 compared with the primary case. Furthermore, the classroom observation rubric detected a 1:1 ratio between the primary case teacher acting to promote student explanations and student evidence of generating explanations within the primary case, compared to a 2:1 teacher to student explanation ratio within lecture 2 (and a 4 :1 teacher: student ratio within lecture 1). In addition, when examining total frequencies, the primary case produced the highest average number of students generating explanations in chemistry per lesson unit time compared with lecture 2 students (and lecture 1 students). These results suggested that although the primary case teacher and the lecture 2 teacher were both observed asking students to generate explanations of scientific phenomena, only the primary case teacher succeeded in consistently triggering a student response.

I observed, on the other hand, the lecture 2 instructor quickly answering his own questions with an explanation rather than waiting or guiding students to respond. Thus, although the majority of surveyed students in all three classes agreed with the statement,

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[9] A slightly higher average number in lecture 2: approximately 6.6 teacher activities to promote or model generating ideas per lesson unit time in Lecture 2 vs. average of 5.1 teacher activities to promote or model generating ideas per lesson unit time in the primary case.

"I have been asked to construct explanations about scientific information or observations during class", it may not be surprising that a significant difference emerged on the CAT post-survey between the primary case and the lecture classes on this item:

> The majority of students in the primary case agreed to the statement, "I have been asked to construct explanations about scientific information or observations during class". There were significantly less students who agreed to this same statement in the lecture 2 class (p=0.007) and the lecture 1 class (p=0.00). There were no significant differences on this statement between lecture 1 and 2 classes.

Thus, it was calculated that on average, the primary case teacher acted to promote or model explanations in chemistry in an approximately equivalent ratio to the lecture classes. It was observed, however, that students constructed explanations over 4x more often in the primary case than Lecture 1 and almost twice as often than the Lecture 2 class. This finding for another process may lend further support to the hypothesis that the lecture 2 instructor was asking and answering questions thereby short-circuiting student explanations in chemistry.

<u>Teacher guidance strategies.</u>

Hypothesis 7. Students in lecture 2 were less engaged in processes than students in the primary case because the teacher activity structures in the primary case evoked a greater student response than teacher activity structures in lesson 2.

One of the observable differences that was detected in the implementation of the GD approach to instruction between lecture 2 and the primary case was that the lecture

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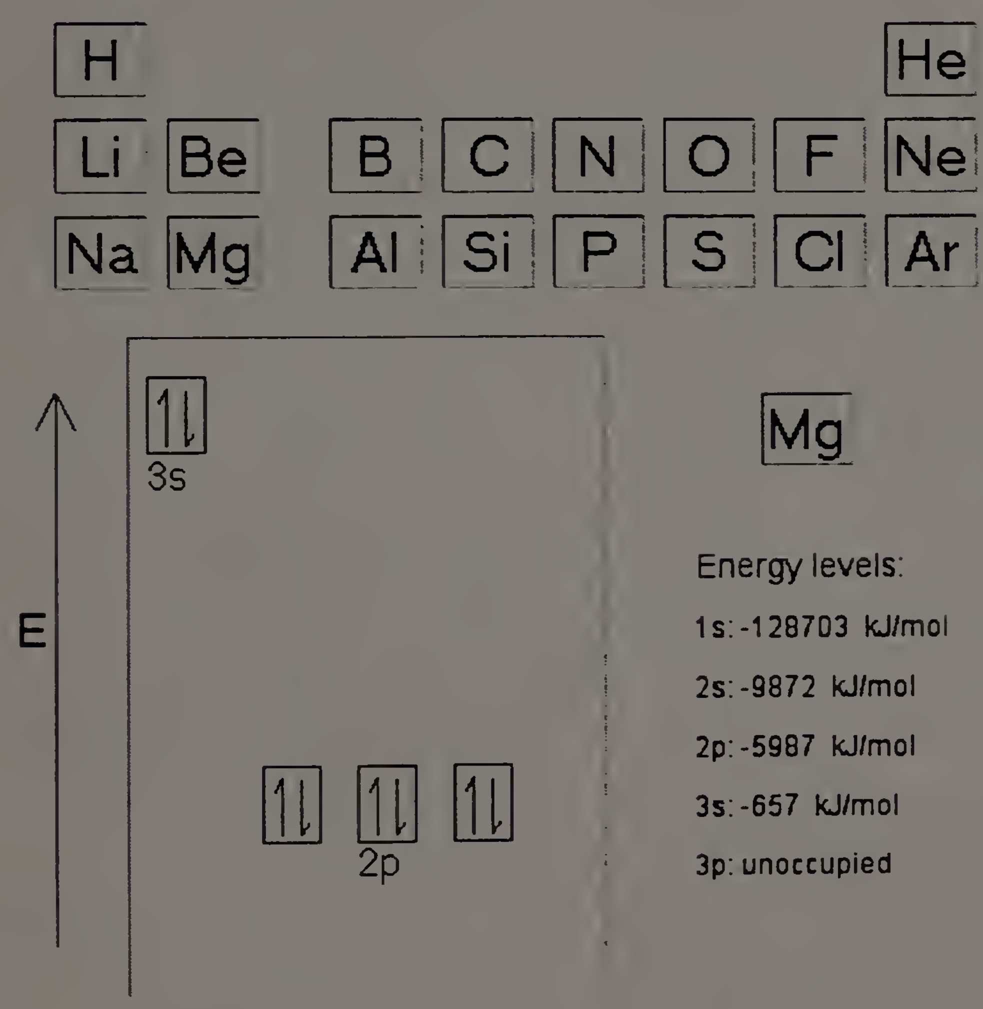
[10] A slightly higher average number in lecture 2: approximately 3.3 teacher activities to promote or model generating explanatory models per lesson unit time in Lecture 2 vs. average of 2.5 teacher activities to promote or model generating explanatory models per lesson unit time in the primary case.

2 instructor was not observed coupling guidance strategies with teacher activity structures. These guidance strategies may have served to encourage and amplify student responses to teacher activity structures, thereby increasing the number of observable instances of student processes that were recorded by the classroom observation rubric.

The data revealed that for generating ideas in chemistry, on average, 5 instances of teacher actions to promote or model generating ideas per lesson unit time in the primary case appeared to trigger, on average, close to 5 observable instances of student evidence of generating ideas per lesson unit. This observation in the primary case could be compared with observations in lecture 2 where close to 7 observable instances of teacher actions to promote or model generating ideas per lesson unit in lecture 2 appeared to trigger only an average of 3 instances of student evidence of generating ideas per lesson unit.

In the primary case, the teacher activity structure of generating relationships was observed to be generally coupled with a guidance strategy such as: the extreme case, incremental values, the comparison, and asking why questions. For example, in the following teacher-student interaction in the primary case, the teacher asked students to gather information from the Chemland orbital energies simulation to construct a relationship between orbital energies and nuclear charges on the periodic table. The teacher used the words "right across" and "all the way down" as extreme cases to help students generate a relationship. Students generated the relationship that orbital energies get lower as you go across the table and all the way down. The teacher introduced discrepant information by pointing out that the orbital energies are going up as you go all the way down the periodic table. The teacher asked students to evaluate this discrepant information. The evaluation activity was coupled with the teacher asking a why question and adding content information (think about effective charge). Students responded by stating that there are more protons (as you go across the periodic table), and so the electrons are held more tightly. Students modified their initial relationship to include electron affinity as a causal factor. Thus, specific teacher guidance strategies such as extreme cases, why questions, and additional content information were associated with the main teacher activities in the primary case.

Eg. Lesson in the primary case.
T Go to Chemland's orbital energies simulation. What happens to the energies as you go right across a period and all the way down?



S7 The orbital energies get lower as you go across.
T What happens as you go down?
S7 The orbital's energy goes down?
T But the energies are going up! Why is that?
[S discussion in groups ensues]
T Why? Think about the charge to charge interaction with the nucleus.
S8 As you go across the table [periodic table], aren't the orbitals getting bigger, that is, they have more electrons?
T Is the radius going up? Think of effective charge.
S9 Well, there may be electron shielding as you go further across [the periodic table]. There are more protons too and that leads to a higher Zeff. So there are more protons, the electrons are held more tightly.

But the coupling of specific teacher guidance strategies with teacher activities was not consistently observed in lecture 2's implementation of the GD approach instruction. For example, there did not appear to be evidence of use of extreme cases, comparisons, or incremental values in this typical teacher-student interaction in lecture 2:

> T If I have very little mass, what happens? Runs gas laws simulation and increases the mass. What happens if I increase the amount of gas in order to keep pressure constant? The volume increases.
> T increases temp on simulation
> S Volume.
> T Volume increases. Why?
> T provides an explanation.

Thus, the lecture 2 instructor was acting to promote or model generating ideas in chemistry twice as often as students were responding with an explanation. In the primary case, however, it was observed that there was close to an equivalent ratio between teacher actions to promote or model generating ideas and student evidence of generating ideas per lesson unit time. This difference in student responses to teacher activities may have been because teacher activities in the primary case were augmented with specific guidance strategies, and teacher activities coupled with specific guidance strategies may have amplified the student response in the primary case.

Lecture 2 teacher requests less.

Hypothesis 8. Students in lecture 2 were less engaged in processes than students in the primary case because the teacher in lecture 2 was asking students to do less process activities.

I discovered that for the process of quantitative problem solving, the average number of teacher instances of quantitative modeling were observed less frequently in lecture 2 than in the primary case. On the other hand, for the quantitative problem solving process in the primary case, the primary case teacher was observed doing on average 2 activities per lesson unit time to promote or model quantitative problem solving compared with an average of 1 teacher activity per lesson unit to promote or model quantitative problem solving in lecture 2. Consequently, the comparatively lower frequency of teacher instances designed to trigger quantitative modeling in lecture 2 may have led to the comparatively lower frequency of student responses of quantitative modeling measured in the lecture 2 classroom. Indeed, the classroom observation rubric confirmed a difference of students analyzing data from a graph or a table 4 times more often in the primary case than students in the lecture 2 class. It may not be surprising then that significantly more students from the primary case agreed that, "I was frequently asked to analyze data from a graph or table in the class" than students surveyed in the lecture 2 class ($p=0.00$) (and significantly more surveyed students from the lecture 2 class agreed with this survey statement than surveyed students from the lecture 1 class ($p= 0.001$). Thus, lower frequencies of teacher instances of process activities may have produced lower levels of student engagement in lecture 2 compared with the primary case. Since we detected this finding only for the process of quantitative problem solving, this hypothesis cannot explain the lower engagement with other processes such as generating explanations that emerged in lecture 2.

4.11.8 Discussion of alternative hypotheses

There were a number of factors that may have contributed to the finding that student processes were detected in lower frequency for lecture 2 students than primary case students. Although teachers in both the lecture 2 class and primary case attempted the GD approach to instruction, three differences between the two cases became immediately apparent with classroom observation. Firstly, lecture 2 students did not interact with the software directly; rather the lecture 2 instructor demonstrated computer use because he was in a large lecture theater with only one demonstration computer.

The primary case, however, was conducted in an electronic classroom, with one computer available for every two students. Students were observed interacting with the computer in pairs. Secondly, according to the CAT pre-survey results, Lecture 2 students were less interested in chemistry as they entered and completed the introductory chemistry course compared with primary case students. Thirdly, Lecture 2 students were enrolled in an introductory chemistry course with over 120 students; the primary case students were enrolled in an introductory chemistry course with 33 students. A demonstration computer, lower level of student interest, and a larger classroom size were three factors that distinguished the lecture 2 class from the primary case.

Although teachers in both the lecture 2 class and primary case attempted the GD approach to instruction, upon closer examination of the classroom observation notes and the classroom observation rubric, two additional differences between the lecture 2 class and the primary case emerged: the lecture 2 teacher was observed doing *more or an equivalent* number of teacher actions to promote or model generating ideas per lesson than the primary case teacher, but there was still a lower frequency of students' generating ideas in lecture 2; and for quantitative problem solving, the Lecture 2 teacher was observed doing *less* teacher actions to promote or model quantitative problem solving than the primary case teacher, and there was a lower frequency of students' quantitative problem solving in lecture 2.

Based on this information comparing the primary case and lecture 2, I explored several hypotheses to explain the lower frequency of student engagement with processes in lecture 2 compared with the primary case. Students working in computer demonstration mode, a lower student interest in chemistry, and a larger classroom size were three factors that distinguished the lecture 2 class from the primary case and may have lowered the average frequency of student processes per unit lesson time for lecture 2 students compared to primary case students.

These factors that distinguished the lecture 2 class from the primary case may be difficult to change. Since the admission policies to introductory chemistry will unlikely change from year to year, it may be reasonable to suggest that from year to year, differences in interest in chemistry may be perceptible between the lecture 2 class and the primary case. Since the chemistry department at this institution enrolled over 2000 students per semester in its introductory chemistry courses, it is logistically difficult for all of the introductory chemistry student body to use the small electronic classroom. The large lecture theater will likely continue to house introductory chemistry students in the near future. It appears that the use of the computer in demonstration mode will also be retained. Thus, a lower interest level of the students, the larger classroom size, and working in demonstration mode may be three factors that influenced the decreased student response to the GD approach in lecture 2, but these distinguishing factors may be difficult to change in the near future at this institution.

Although there may have been a number of factors that lowered the average number of student responses to the GD approach to instruction in lecture 2, we also observed 4 other instructional differences between the lecture 2 teacher's implementation of the GD approach to instruction compared with the primary case implementation of the GD approach to instruction. Firstly, the lecture 2 teacher did not incorporate small group activities in the course like the primary case teacher. Secondly, the lecture 2 teacher was observed answering his own questions 4 times more often than the primary case teacher, short circuiting student generation of ideas in chemistry and student construction of explanations in chemistry in lecture 2. Thirdly, teacher activities to promote or model generating ideas in chemistry was not observed to be coupled with guidance strategies in lecture 2 as they were in the primary case, and fourthly, teacher actions to promote or model quantitative problem solving were detected in lower frequency in lecture 2 than the primary case. These four instructional differences in the approach to GD instruction in lecture 2 may have also explained why students in lecture 2 were not observed responding to GD process activities in the same frequency as the primary case students.

The instructional differences in the implementation of the GD approach between lecture 2 and the primary case were perhaps a reflection of the modifications to instruction that one could expect when a different teacher uses the GD approach to instruction. Although these instructional differences did not represent major departures from the general teaching activities of the GD approach to instruction compared to the primary case, it is plausible to suggest, however, that, in addition to the differences in class size, student level of interest, and use of computer in demonstration mode, these four instructional differences in lecture 2 from the primary case may have produced a concomitant lower frequency of average student responses per lesson unit time to activities in lecture 2. Fortunately, unlike the first 3 factors, these four instructional differences in lecture 2 are easily rectifiable. For example, in an effort to increase student evidence of generating ideas and constructing explanations, the Lecture 2 instructor could attempt small group discussion in the lecture theater with student polling after discussion. In an effort to increase student responses to GD activities when immediate answers are not forthcoming from the students, the lecture 2 teacher could attempt to increase wait time and couple teacher activities with more guidance strategies. These strategies may serve to amplify student response and student engagement within the lecture 2 setting.

Contrasting cases between lecture 2 and the primary case highlighted three additional conclusions: firstly, the GD approach to instruction could be modified for instruction within a large lecture theater setting. Secondly, it was hypothesized that it was probably a combination of factors that contributed to the primary case's comparative success at engaging students in fundamental processes in science throughout the semester. Finally, the overall evidence seemed to indicate that the GD approach to instruction in the primary case was successful at targeting and engaging students in several of the fundamental processes associated with scientific inquiry compared with other approaches we observed in the chemistry department.

4.12 Process skills vs. content coverage

Even though the GD approach to instruction was observed to be relatively successful at engaging students in the fundamental processes of science throughout the semester, one of the concerns of implementing such an approach to instruction is that teachers would not be able to simultaneously cover the content in their course' syllabus. In an effort to gauge whether content was compromised in the primary case, I compared several content-based indicators in each class: a comparison of the types of content based questions asked by the teacher in the three classes, a comparison of the delivery of field specific content information in the three classes according to the classroom observation rubrics, and a comparison of the content coverage in the syllabi of all three classes. The results are reported in the next sections.

4.12.1 Comparing question types

This section compares the types of content based questions asked by the teacher in the three classes. All of the questions and answers in each lesson were hand counted twice. The questions were grouped into questions that originated from the teacher or the student, and answers that were responded to by the teacher or the student. All questions recorded in the observation notes were included in the data set except for administrative questions. Administrative questions were questions that were about homework assignments and due dates.

An average of the number of counts per lesson was tabulated. These averages allowed us to compare the frequency and types of questions that the primary case teacher asked during instruction, with the frequency and types of questions that the lecture instructors asked during instruction. These comparisons are listed below in this order:

Table 30. Counts of average number of question/answers per lesson.

Averages per lesson*	Teacher answers			Student answers		
	Primary Case	Lecture 1	Lecture 2	Primary Case	Lecture 1	Lecture 2
Teacher questions	1	4	8	16	21	12
Student questions	3	7	5	0.3	0.3	0

* Note: lessons are not equivalent in time. The lesson period was 50' in the lecture classes and 75' in the primary case.

The highest average number of teacher questions with student responses per lesson was Lecture 1 (average 21 per 50 minute lesson), followed by Lecture 2 (average 12 per fifty minute lesson), and finally, the primary case (average 16 per 75 minute lesson). I observed a "rapid fire" mode of questioning in the lecture classes compared with the primary case.

The types of instructor questions were further subdivided into two possible categories: content based questions or process based questions. Content based questions were questions from the teacher that asked students for factual information to respond with that information with field specific information. Process based questions were considered to be questions from the teacher that asked students to generate ideas, gather information, critique results or conclusions, analyze primary literature, communicate through science writing and presentations, analyze a quantitative problem. Administrative questions were excluded from both categories.

Table 31. Two categories of teacher questions to students.

Content Questions	Process Questions
What does properties mean?	What would be the bond angle that you would predict for resonance structure 1draws a cloud picture of ^{24}Mg and says what's wrong with this picture based on Coulomb's Law? resonance structure 2?
What makes a metal a metal and a non-metal a non-metal?	What is the reason why He is different from O_2?
What's the single distinguishing characteristic of all antibonding?	What will happen to number of collisions if I double the number of moles?
	What are the trends that occur as you increase temperature for the phases of the elements?

Administrative questions by the instructor, such as, "Any questions about the homework?" were excluded from coding and analysis.

Classroom observation notes were reviewed and the number of process based and content based questions were hand counted. The hand counts were checked twice. The hand counts could not be checked against the observation rubric, since each process and content category coded for all instances of instructor actions to promote or model the activity, and promoting or modeling the activity was not limited to the teacher asking a question to students. An average number of counts per category per lesson period was tabulated and reported in Table 32.

Table 32. Types of teacher questions per lesson.

Average Q/lesson	Primary case	Lecture 2	Lecture 1
Content Questions	8	15	24
Process questions	9	5	1
Total teacher q	17	20	25

* Note: lessons are not equivalent in time. The lesson period was 50' in the lecture classes and 75' in the primary case.

1. Lecture 1 instructor asked approximately 24x more content oriented questions in proportion to process oriented questions on average in a fifty minute period.

2. Lecture 2 instructor asked approximately 3x more (three-fold) content oriented questions in proportion to process oriented questions on average in a fifty minute period.
3. The primary case teacher asked an approximately equivalent number of content oriented questions in proportion to process oriented questions on average in a seventy five minute period.
4. The primary case teacher asked an average of 9x more process questions approximately per lesson than the Lecture 1 instructor and 2x more process questions than the Lecture 2 instructor.
5. The lecture 2 instructor asked students twice as many content questions approximately per lesson than the primary case teacher, and the lecture 1 instructor asked 3x as many content questions approximately per lesson than the primary case teacher.

Based on 1 and 2 from the list above, the lecture instructors predominantly asked content/factual questions to students rather than questions that promoted inquiry, compared with the primary case teacher who asked an approximately equivalent number of content oriented questions in proportion to process oriented questions on average in the class. The primary case teacher asked students an equivalent ratio of process to content questions, whereas both the lecture instructors asked students more content and fact oriented questions than process oriented questions in a rapid fire mode.

4.12.2 Comparing content delivery

Not surprisingly, the classroom observation rubric produced a similar difference in the ratios of field specific bodies of knowledge given by the teacher.

Table 33. Ratios of content.

Ratios of activities observed per time period	Primary case	Lecture 2	Lecture 1
Teacher delivers field-specific bodies of knowledge; gives content information in any form	1	2	4

4.12.3 Comparing content coverage

From the above content indicators, it would appear that the primary case teacher was delivering less content information in the course compared with lecture 1 and lecture 2 classes; however, when the content coverage was examined, a different finding emerged:

Table 34. Contrasting content in the three cases.

Ratios of content delivery per lesson	Primary case	Lecture 2	Lecture 1
Teacher delivers content information	1	2	4
Content: Process questions asked by the teacher	1:1	3:1	24:1
Chapters of text covered	11	10	10

The primary case teacher fulfilled the content goals for the course by covering the required chapters in the text and completing the requirements of the department-wide introductory chemistry syllabus. The primary case teacher may have been able to cover the content by assigning work outside of class. Students were expected to complete OWL electronic homework assignments and read the text after the topic had been discussed in class. In addition, students in the primary case completed the same OWL assignments as the lecture classes and the majority of students successfully passed their final exams. Thus, the content requirements for the course were fulfilled in the primary case.

4.12.4 Findings from classroom observations

The purpose of this study was to analyze an instructional strategy in an introductory chemistry class to understand how it may have been fostering scientific inquiry. The study focused on three main research questions:

1. What were the instructional strategies and interactions in this class?
2. What were the major learning processes that were triggered during instruction?
3. How did the teacher's behavior support learning?

In order to identify the instructional strategies and interactions in this class, a classroom observation protocol was designed and a classroom observation instrument developed to record classroom events. After three semesters of classroom observations (20 classes observed in total) in the primary case, a consistent pattern of instruction emerged. This pattern of instruction was called the "Guided Discovery" (GD) approach to introductory chemistry and consisted of 4 main phases of instruction, 6 key activity structures and 15 teacher guidance strategies. The 4 phases of instruction included background information, compile information between two variables, generate a relationship between the variables, and evaluate and modify the relationship based on any new information. The phases of generating, evaluating, and modifying relationships in chemistry were referred to as GEM, and because the evaluation and modification phase were observed to cycle between evaluation and modification repeatedly, the phases were referred to as GEM cycles. Thus, the guided discovery approach to introductory chemistry consisted of the teacher triggering GEM cycles in the primary case.

Each phase was characterized by the following 6 teacher activities. During the background information phase, the teacher was observed providing initial content information. During the compile information phase, the teacher typically asked students to compile information between two variables from the interactive computer tool, Chemland, and immediately afterwards, during the generate relationship phase, the teacher asked students to find the trend in the information they had just gathered. After students generated a relationship between two variables, the teacher was observed triggering an evaluation and modification of the initial relationship by providing new information from the interactive computer tool. This information was observed to be discrepant information, an extreme case, or confirmatory information. Evaluation and modification of the initial relationship was a phase of instruction that was observed repeatedly. Thus, the GD approach contained 4 main phases of instruction that appeared to trigger iterations of GEM cycles in the primary case.

Within each of these phases of instruction, there were structured teacher activities. The teacher triggered the GD approach by providing some background content information before introducing students to an interactive computer tool. After demonstrating how the computer tool could be used to produce information, the teacher challenged students to compile information between two variables in small groups and to find the trend or the relationship in the large set of data. The next phase was an evaluation and modification phase, where the teacher sparked the evaluation and modification of the initial relationship by introducing new information. This information could be discrepant information, an extreme case, or confirmatory information. Thus, the teacher triggered GEM cycles with key activity structures such as finding the trends and providing discrepant information. Approximately two complete GEM cycles were observed per 75-minute class with a total of 52 GEM cycles occurring throughout the semester in the primary case.

Throughout these phases of instruction in the GD approach, the teacher associated activity structures with specific teacher guidance strategies. Fifteen different guidance strategies were identified and included: analogies, constrained variables, the extreme case, semiquantitative relationships, incremental values, the comparison, why, what's wrong, predict, work back from the data, see if this relationship holds true, design a new test, consider new variables, and find more information. Thus, specific teacher guidance strategies were a part of the GD approach to instruction in the primary case.

The chemistry department at this university became increasingly interested in innovations designed to facilitate instruction. One of the innovations they introduced into the introductory chemistry classroom was the integration of interactive computer tools. The suite of interactive computer tools was called Chemland. Chemland did not replace the laboratories associated with introductory chemistry, but rather dynamically represented the results of simulated lab experiments or the behavior of atoms of molecules under conditions that were not normally observable. Furthermore, Chemland was not designed to tutor the student, so with each phase of instruction, the teacher guided students to use the software. Consequently, the teacher was observed guiding students to select relevant variables, gather information between two variables, dynamically regenerate graphs and compare color coded curves, push variables to their extremes or in increments, design new tests and observe multiple representations of chemical reactions and molecules with Chemland. The GD approach was observed to be fully integrated with Chemland software at each phase of instruction.

The three main findings of the classroom observations of the primary case were that the GD approach to instruction described the central pattern of instruction we observed in the primary case. The GD approach to instruction was characterized by GEM cycles, teacher guidance strategies and the full integration of Chemland interactive computer tools, and the GD approach to instruction was observed to be sustained throughout the semester in the primary case.

We observed students responding to the GD approach to instruction in the primary case. Using the classroom observation rubrics, contiguous teacher - student sequences were detected in each lesson throughout the semester in the primary case. There was documentation of teacher activities to promote or model these processes associated with student evidence of the same processes in the following six categories: generating predictions (simple hypotheses) or rules concerning simple relationships between variables; generating explanations or conceptual models (causal or mechanistic explanations – why or because; evaluating logical, empirical, or conceptual consistency; quantitative problem-solving and modeling (using numerical models in science); field-specific bodies of knowledge, and field-specific lab skills. The classroom observation rubrics appeared to confirm the classroom observation notes that teacher activities associated with the GD approach to instruction seemed to trigger student responses in the primary case.

The classroom observation rubrics also suggested that students' responses seemed to indicate a sustained engagement with several of the fundamental processes commonly associated with scientific inquiry. Evidence of student responses that were coded in the classroom observation rubric included observations of students generating relationships between variables, generating explanations or conceptual models about chemistry, evaluating the logical, empirical, or conceptual consistency of the relationships in chemistry, and quantitative problem-solving and modeling were evident throughout the semester. Taken cumulatively, these findings seemed to indicate that the GD approach to instruction in the primary case triggered a sustained student response, and that student response seemed to indicate that students were engaged with several of the fundamental processes commonly associated with scientific inquiry.

Even though several fundamental processes commonly associated with scientific inquiry were observed being sustained in the primary case, there was no evidence of student of engagement with several other processes that have also been commonly associated with scientific inquiry. For example, there was no evidence of students in the generating their own questions for inquiry, gathering and organizing data during experimentation or critiquing experimental design, comparing theoretical frameworks, reading primary literature, communicating in science with presentations, or conducting statistical analyses of data in the primary case. This finding suggested that several processes associated with scientific inquiry were not triggered by the GD approach to instruction in introductory chemistry. Thus, I could not conclude that students were engaged in all of the processes associated with scientific inquiry; however, several fundamental processes commonly associated with scientific inquiry were documented throughout the course of the semester in the primary case. Analysis of the primary case also revealed that student engagement with several fundamental processes associated with scientific inquiry was sustained without compromising content coverage in introductory chemistry in the primary case.

In contrast to other introductory chemistry classes in the same department, classroom observations of the primary case and two other introductory chemistry classes uncovered a pattern of instruction in the primary case that was markedly different from two other introductory chemistry classes in the department (referred to as Lecture 1 and Lecture 2).

Contrast between the GD Approach with Lecture 1 and 2 approaches to instruction. There were numerous differences between the lecture classes and the primary case, and one of those differences also appeared to be the method of instruction. Although both primary case and lecture teachers shared the same syllabus and reported similar content and process goals for their students, their methods of instruction in the lecture 1 class was observably different.

A linear pattern of instruction emerged from classroom observations of the lecture 1 instructor where the instructor consistently introduced a term at the start of class, then conducted a classroom demonstration or described relevant examples, and, if there was time remaining, modeled how to solve a chemistry problem. The approach to instruction in lecture 1 was observably different from the teaching strategies that characterized the GD approach to instruction in the primary case because there was limited evidence of the lecture 1 instructor asking students to generate relationships, evaluate and modify them in light of new information. In this regard, the activities in the primary case could be considered distinctive compared with the more traditional approach to instruction that was represented by lecture 1.

On the other hand, the approach to instruction in lecture 2 was similar to the primary case. Many of the same teacher activities in the primary case were observed with similar frequencies as in the lecture 2 class; however, the frequency of student responses to these activities was measurably lower in the lecture 2 class than student responses to these activities in the primary case. This finding indicated that even though the GD approach to instruction was attempted in lecture 2, lecture 2 produced a lower level of student engagement with these processes compared with the primary case. The lower frequency of student responses in lecture 2 may have been caused by a number of factors that distinguished this class from the primary case, including the larger size of the lecture 2 class, lower level of student interest in chemistry in lecture 2, the absence of small group discussion as a mode of interaction in lecture 2, and the use of a single demonstration computer in lecture 2 as opposed to multiple computers in the primary case. But it was also discovered that the lecture 2 instructor provided 40% of the answers for questions initially asked to the students, much more than in the primary case, and some of which may have otherwise launched student inquiries that generated ideas in chemistry and constructed explanations as they had done in the primary case.

This finding highlights the need for explicit guidance strategies for teachers when student answers are apparently not forthcoming. Guidance strategies were noticeably absent in lecture 2's instruction. Therefore, a recommendation suggested to lecture 2 was to couple teacher activity structures with the guidance strategies in an attempt to trigger student responses and amplify frequencies of student engagement with the fundamental processes of science.

Thus, contrasting the primary case with lecture 1 suggested that dimensions of the GD approach to instruction could be considered a unique approach to instruction , compared with the more traditional approach to introductory chemistry instruction that was represented by lecture 1. Contrasting the primary case with lecture 2 further suggested that such instructional methods can be transferred, in part, to a large lecture setting. Finally, it was hypothesized from contrasting cases that it was probably a combination of factors that contributed to successful student engagement with some of the fundamental processes of science in the primary case, including the effective use of specific teacher guidance strategies to amplify student responses.

To place the primary case into an even broader context, a qualitative profile of produced in the next figure where the GD approach to instruction with Chemland was compared in the context of traditional modes of instruction as represented by lecture 1, demonstration modes of instruction as represented by lecture 2, and a hypothetical discovery mode of inquiry instruction with computers. The hypothetical discovery mode of inquiry instruction could be represented by cases similar to Thinkertools (White and Frederiksen , 2000), WorldWatcher (Edelson, 2001), and the Air pollution learning environment (Singer, 2000).

The comparison was based on several possible classroom indicators: content coverage as represented by the field specific content indicator bar, the number of different student inquiry processes observed as represented by the number of different process skills indicator bar, the degree of teacher scaffolding of inquiry as represented by the scaffolds for processes indicator bar, variable modes of classroom interactions such as small group interaction, oral presentations, experimentation, or debates as represented by the variable modes of classroom interaction indicator bar and variable modes of computer use such as using the computer as a source of information, communication with experts, tutoring, database and statistics, modeling, and assessment. A darker shading of each bar indicated a greater sign of the indicator. Taken together, the indicator bars produced a qualitative profile. The qualitative profiles that emerged for each kind of instruction placed the GD approach to instruction with Chemland into the middle of the inquiry spectrum. These profiles are represented by Figure 7 below to conclude this section on classroom observations.

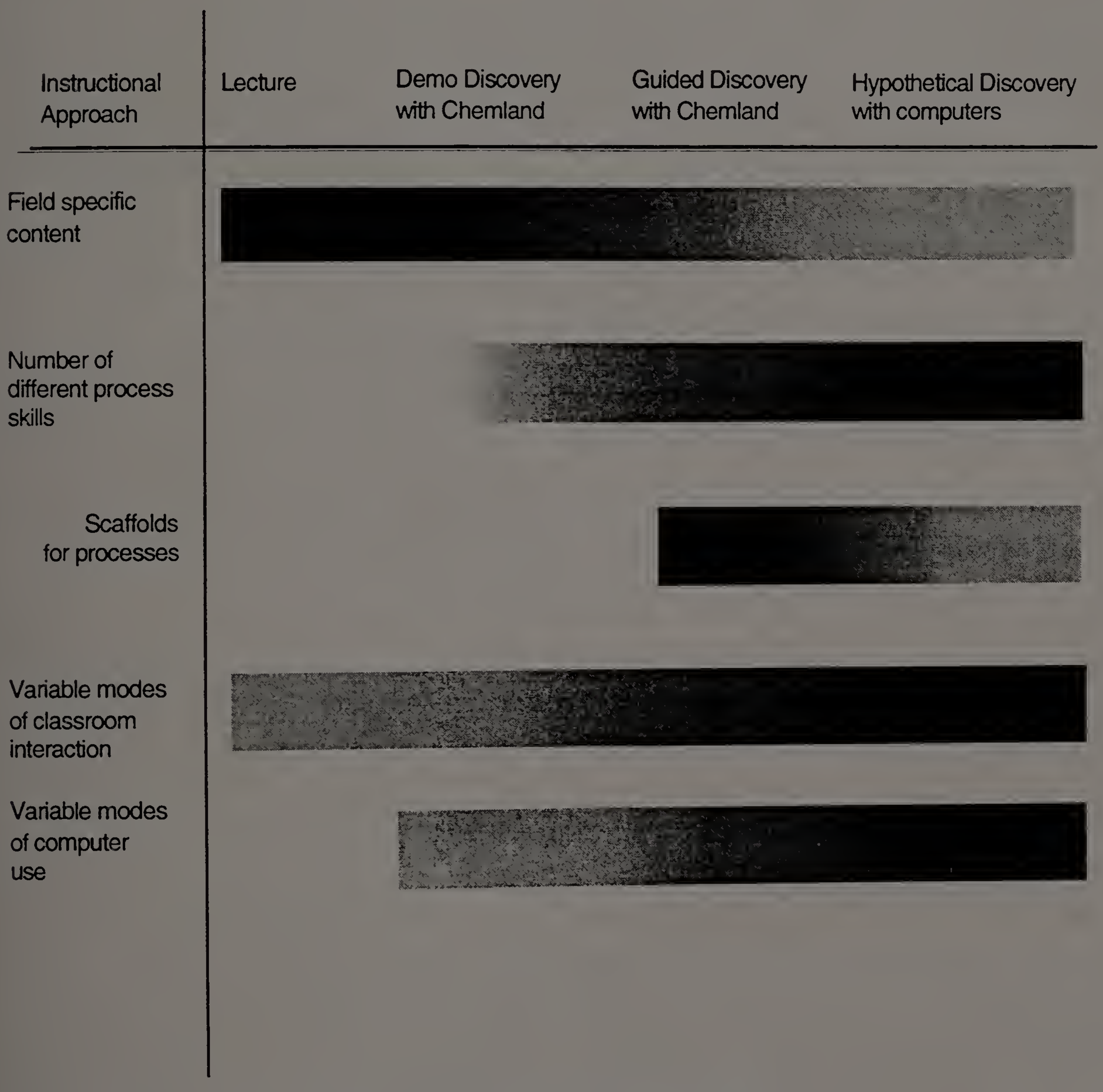


Figure 7. Spectrum of instructional approaches to inquiry.

4.13 In-depth pair sessions

4.13.1 Purpose of the in-depth pair sessions

The CAT post- surveys had revealed that teacher discussion with students was ranked as the most important learning experience for students in the primary case (n=21) out of 9 possible choices. The second most important learning experience for surveyed students in the primary case was ranked as the classroom simulation (n=21) out of 9 possible choices. The laboratories and reading the textbook ranked as the last two choices respectively in the primary case. Thus, students in the primary case reported that teacher discussion with them and the classroom simulations were their top two learning experiences in the class.

While it was possible to identify some of the critical components of teacher discussion with the students, such as the teacher's key activity structures and specific guidance strategies using the classroom observation notes and classroom observation rubric, it was more difficult to capture small group discussion in response to these activities in the primary case, as suggested by the low frequencies of student to student discussion detected from the classroom observation notes in Table 35.

Table 35. Counts of average number of question/answers per lesson.

Averages per lesson*	**Teacher answers**			**Student answers**		
	Primary Case	**Lecture 1**	**Lecture 2**	**Primary Case**	**Lecture 1**	**Lecture 2**
Teacher questions	1	4	8	16	21	12
Student questions	3	7	5	0.3	0.3	0

* Note: lessons are not equivalent in time. The lesson period was 50' in the lecture classes and 75' in the primary case.

In order to identify what the major learning processes were that were triggered during instruction in the primary case, there was a need to elaborate on the discussion that was happening with the students in response to instruction in the primary case.

Thus, the purpose of the in-depth pair sessions was to elaborate on students' responses to the guided discovery approach with Chemland in the primary case greater detail than the classroom observations would allow.

An in-depth pair session protocol was designed to document students' learning in response to the GEM cycle (Khan, 2001) in the primary case. During these in-depth pair sessions, the same teacher "taught a class" on boiling points to a pair of students from the class (6 pairs of students from the primary case participated in the in-depth pair sessions) where the teacher, the students, and the interactive computer tools played the same roles that were observed during class, except students were prompted by an interviewer to "think out loud" during instruction. Recording the details of student discussion with each other as they used Chemland and student discussion with their teacher would help us to generate hypotheses about the major learning processes that were triggered during instruction in the primary case.

4.13.2 Episodes of learning

The teacher's activity structures and guidance strategies were designed to trigger student discussion about relationships in chemistry in the primary case. Based on classroom observations, it appeared that teacher activities triggered whole class and small group student discussion in the primary case. The discussion was generally characterized as discussion about relationships in chemistry and the discussion could be coded in the classroom observation rubric. The classroom observation rubric uncovered that students were engaged in several fundamental processes associated with scientific inquiry. This section will focus on, in greater detail, the student discussion in response to these activities and hypothesize additional outcomes as a result of this in-depth analysis. Figure 8 highlights where we are in the chain of the theory.

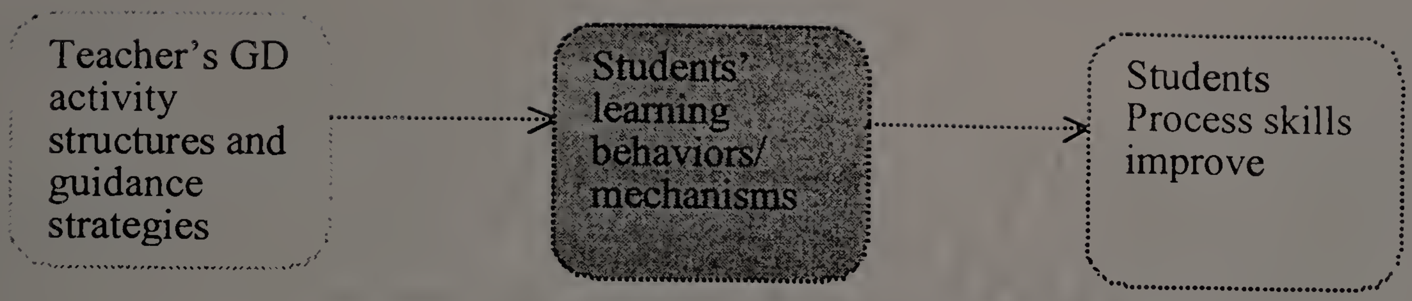


Figure 8. Theoretical mechanism to produce gains in process skills

The theoretical learning mechanism was that the activity structures and guidance strategies embedded in the guided discovery approach triggered student learning trajectories that engaged students in those processes associated with inquiry and may have led to gains in an initial test of those skills. The table below traced one such learning trajectory in response to the guided discovery approach from in-depth pair session 2. The learning trajectory in this example is interjected with CAT post- survey statements from the primary case suggesting the degree of commonality of the learning experience for surveyed students in the whole classroom.

Table 36. Tracing students' learning in an episode with CAT survey results.

Phase of Guided Discovery Approach, the Activity structure, Guidance Strategy	Students' Learning Trajectory	Evidence: Student Discussion Triggered
Background information. Added information, using field specific content and an analogy: Ln 23. T [W]e're going to look at a thing called a Boltzmann plot. A Boltzmann plots a number of molecules on the y-axis versus their speed on the x-axis. So actually, I'll start this up for you. Actually go down here.		

Phase of Guided Discovery Approach, the Activity structure, Guidance Strategy	Students' Learning Trajectory	Evidence: Student Discussion Triggered
Ln 32. T Just click on calculate. So this is a Boltzmann distribution for oxygen O_2 at 300 Kelvin, so what it does is it shows a plot that looks something like this. And so what that means, what this is, is a plot of how many molecules are going different speeds. Ln 35. So what this tells you is a couple of things: not very many molecules go really slowly, not very many molecules go really, really fast, but most molecules go in the middle. It tells you that. It also tells you that at particular, for a particular kind of molecule the temperature not all the molecules go the same speed. They go at a range of speed, so some are going slow, some are going fast. Ln 41. And so it's very much like a plot of cars on a highway. So some cars are going like 90, very few of them are going 90, lots of them are going you know a bunch are going 80, most are going you know 60 or 70, very few are going 30 or 40 or whatever. So it's like if you were watching a highway for a long time. So that's what this is for -gas molecules.		
Compilation of information phase. Showed Boltzmann Distribution simulation, selected variables and displayed the graph. Generation of a relationship between temperature and the		

Phase of Guided Discovery Approach, the Activity structure, Guidance Strategy	Students' Learning Trajectory	Evidence: Student Discussion Triggered
distribution of molecular speeds. Ln 48. T So what we want to do is we want to study where, what the effects are on making changes to the system on these plots on the distribution of molecular speeds. So the first thing we're going to do is we're going to look at the changes that temperature causes, and then we want to explain those. So go ahead and play around with temperature and see what that does.		
	Compiled information from the Boltzmann Distribution (BZD) simulation. Selected two variables: the speed of oxygen at different temperatures.	Ln 57. S2 Well we're going to increase the temperature and see what happens to the curve and the curve is now. S1 Higher. Well it's. S2 It's lower. I Is it higher or lower? S2 Let's clear. S1 Start again. That's the original and then we'll go to (click). Ln 70. S2 Let's go way up. S1 600 and it's lower. S2 Lower, so. S1 We could also go to 200. S2 So now it should be pretty higher. S1 And it's higher.
	Generated a semi quantitative relationship that as temperature increased, molecular speed increased by comparing the graphs (quantitative models of BZD) at two **extreme temperatures**	Ln 82. S2 But basically it seems like the number, the amount of molecule speed. The one's that are going faster increases as the temperature goes up, whereas if it's a really cold temperature [referring to the above extreme case] then the number of molecules going really quickly. S1 Decreases. S2 Decreases. So as temperature

Phase of Guided Discovery Approach, the Activity structure, Guidance Strategy	Students' Learning Trajectory	Evidence: Student Discussion Triggered
		increases molecules speed up. Ln 90. S1 Uh, huh. Speed increases. Ln 104. S1 As temperature increases, speed increases. As temperature decreases, speed decreases.
Evaluation of empirical consistency of relationship by comparing two extreme cases. Ln 117. T Okay so my question is at 600 degrees are all the molecules going faster than all the molecules at 300 degrees? Are all the molecules at 600 degrees going faster than all the molecules at 300 degrees?		
	Modified initial relationship to suggest that include that there is a distribution of speeds.	Ln 121. S1 Not necessarily. S2 No. Uh, uh. S1 It seems like they 're more spread out.
Summary Ln 127. T So there are some molecules at 300 degrees going faster than some molecules at 600 degrees?		
	Summary	Ln 130. S2 Right. S1 That's right.
Summary Ln 134. T But on average they're going faster at?		
	Summary	Ln 136. S1; S2 600 degrees.
Explanation: Ln 138. T Okay, okay good. All right so talk for a minute and see if you can come up with a reason, just		

Phase of Guided Discovery Approach, the Activity structure, Guidance Strategy	Students' Learning Trajectory	Evidence: Student Discussion Triggered
come up with a reason why this happens. Why as temperature goes up does molecular speed go up? So just kind of come up with a reason for that.		
	Explanation: Attempted to produce a causal mechanism for the initial relationship that as temperature goes up, the molecular speed goes up. Student explanation revealed their uncertainty about the role of heat and collisions in this mechanism: did bouncing off of each other, or greater heat, increase molecules' speed?	Ln 143. S1 Okay. S2 Let's see. Ln 147. S1 Because heat makes things go fast, okay heat makes things move faster in general so the molecules will be bouncing off each other. S2 That's right, so there would be. S1 More quickly than they would if it was cold. Ln 154. S2 That's right they'd be moving faster. S1 Uh, huh. S2 They'd be running into each other <u>more.</u> <u>S1 And then they'd bounce off each other and that would just increase their speed more and more.</u> <u>S2 Yeah.</u> <u>S1 So it would make them faster.</u> <u>Ln 167. S2 Just greater heat also would make them go faster. I am not sure what the reason would be for that.</u> <u>S1 The heat.</u> S2 That is the reason: the heat. S1 Just the heat. S2 Yeah. <u>Ln 178. I So are you saying that each molecule moves faster or because of the collisions they end up moving faster?</u> S2 I think the collisions causes pressure to increase if they were like in an area where they were detained because I don't think it would affect their speed necessarily.

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Explanation: Ln 185. T Okay, so you're saying that as the temperature goes up, what's happening?		
	Explanation: Attempted to produce a causal mechanism of changes in temperature and the changes in molecular speed.	Ln 188. S1 The molecules start bouncing off of each other more quickly. S2 They are moving away from each other. Ln 192. S1 Right and because they bounce off each other they start you know moving away from each other more quickly. T Okay. S1 And this is if they were like in a globe or a glass.
Problem solving strategy: think of a single molecule in order to discriminate how a molecule increases its speed. Ln 199 T <u>Say there was just one molecule.</u> If it was just one molecule and the temperature, temperature went up; would anything happen? <u>So there couldn't be any collisions. Would the molecule go faster or slower or not change if the temperature went up?</u>		
	Evaluated the conceptual consistency of the explanatory model	Ln 204. S1 If we stick to our original theory, then I guess it wouldn't change. S2 That's right. S1 There'd be no collision, so.
Problem solving strategy: think of a single molecule in the system. Ln 210. T Okay, so why is the molecule, so if you think about it in terms of a single molecule and you		

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raise the temperature up, <u>why would they bounce of each other more quickly or more often, if each individual molecules isn't going faster?</u>		
	Evaluated the conceptual consistency of the explanatory model	Ln 220. S2 Because heat (click). S1 Because I guess more heat would create more pressure. S2 Or energy. It like, it would give them the ability to. I'm not really sure why that actual.
Problem solving strategy: think of a single molecule in the system. Ln 222. T I was just thinking about what you said that at a higher temperature, they would bounce off each other more, and so I'm trying to think about <u>if individual molecules don't change their speed how could they bounce off each other more, at one temperature versus another temperature, if the individual molecules weren't going faster?</u>		
	Modified original relationship to include pressure as a variable: Students modify initial hypothesis that heat and collisions cause an increase in molecular speed to <u>"heat does increase the speed of each molecule **and then** they also bounce off</u>	Ln 228. S1 Okay we agreed that the collisions were causing pressure and not necessarily a change in the speed, so maybe if heat did increase the speed of a single molecule. <u>S2 So we could say that heat does increase the speed of each molecule and then they also bounce off each other if there's a lot of them together, and that would make them go even faster.</u> <u>Ln 236. S1 And that's why heat and pressure are related, and heat and speed are related.</u>

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	each other"	

The majority of students (n=21) agreed with this statement, "I understand how scientists assess and modify theories about unobservable processes."

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Summary: Ln 239. T Okay, so the way you wound up thinking about this is as temperature goes up individual molecules do go faster and that's kind of the plot you're seeing. S1 Okay. Ln 245. T They do bounce off each other more but that actually doesn't increase pressure. Where the pressure comes from actually is the molecules bouncing off the walls of whatever they're in. S1 Uh, huh. Ln 251. T So they do collide more with each[other] and with the walls, but it's the collision with the wall that actually causes an increase in pressure, not collisions with each other. So the increase in this curve is that the individual molecules are going faster as temperature goes up, so because they have more energy. So more energy makes things go faster.		
Generation of a relationship between the		

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nature of the molecule and the temperature. Ln 270. T Okay so the next thing we want to do is we want to actually explore not temperature, but the nature of what the molecule is. What the gas is made out of. S1 Uh, huh. S1 Uh, huh. T And so what we have is we have the ability to lead the temperature to a particular thing and look at different gases. So why don't you go ahead and look at different gases and see if you can figure out a trend, so I would clear the plot first of course and then go ahead and do the gases. (click)		
	Compiled information from the BZD simulation. Selected two variables: different elements and compounds of different weights and speed.	Ln 282. I What's your strategy? S1 Just to. S2 We're just going to put them on here as we can tell that as we move down here from helium to neon to nitrogen to oxygen to carbon dioxide the umm. S1 How the speed is changing with each one. Ln 292. S2 Well yeah, the speed's changing, but we're also looking as we go down here the weight of each one of those molecules or compounds is increasing.
	Generated a semi quantitative relationship that as mwt increased, molecular speed decreased by comparing the curves of different	S2 And so as the grams per mole increases the number of grams per mole decreases the speed. S1 The speed decreases. S2 In general decreases. I And how can you tell? Ln 303. S1 Well because this is a 131 grams per mole and that's the

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	compounds using the graph (quantitative models of BZD).	heaviest and that's in yellow and it's only 500 feet. S2 And the largest number of the molecules in this graph here show that there at really low speeds opposed to the majority of the helium atoms are at a higher speed over here and they're only 4 grams. S1 Uh, huh. Ln 309. T Okay so the rule you're coming up with is what? S1 That as weight increases speed decreases.

According to the CAT post-survey, 76% of surveyed students (n=21) agreed and 4% disagreed that "Qualitative rules or concepts that are descriptive and non-mathematical help me understand chemistry."

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Did not intervene	**Constructed an explanation** for why as weight increased, speed decreased because, according to the students, it would take a lot more energy to move that much more mass.	Ln 317. S2 And that would make sense because we just said that as energy increases or heat increases they're more able to speed up, S1 Right. Ln 322. S2 And therefore it would take a lot more energy to move that much more mass. S1 Plus you know just from in general that weight is harder to move. T Okay so. S1 Something heavier is harder to move.
Generation of a quantitative relationship between speed, temperature, and mass. Ln 338. T Okay, so if we were going to make an <u>equation</u> to put these two		

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things together, any idea of what it might look like? Like speed is related to what? Like say we wanted to make an equation for speed. Speed equals something, some function of temperature and mass, or is proportional to. Talk about that for a minute. See if you can come up with some vague equation that does that.		
	Generated a quantitative relationship that speed is proportional to temperature, and speed and inversely proportional to mass. Examined the graphs (quantitative model of BZD) to determine that speed is proportional to temperature and inversely proportional to mass.	Ln 345. S1 Speed is proportional to temperature because as temperature increases speed increases. S2 That's right speed is proportional to. S1 It's like inverse isn't it. S2 Yeah it would be inverse for mass as speed increases mass decreases. S1 Right. Ln 357. T So what am I writing? S1 Speed is proportional to temperature. Ln 361. S2 Yeah. S1 And then speed is inversely proportional to mass. T Okay. I How did you figure out that it was inversely proportional to mass? Is that something that you remembered from high school? S2 No, that's, Ln 372. S1 No, just. S2 Yeah. We can tell I mean just looking at the graphs we can see the trend that has. I mean it would make sense not looking at the graph, but it seems a lot more clear now that as the. S1 As one goes up the other goes down, so it's inverse. S2 Yeah because you need. T Based on? Ln 384. S1 Based on this.

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		S2 Yeah, based on the graphs you can see.
Evaluation of empirical consistency of the quantitative relationship between speed and temperature that was initially generated by the students, using incremental values: Ln 388. T What I want to do is I want to look at the speed temperature thing again in a little more detail. So go back and make a graph at 300 and 600. Actually you have to do it for one of the heavier molecules. S1 Okay. Ln 394. T Yeah I want it to be exactly double like 300, 600.Okay so now look at that fairly carefully and think about whether or not you think the speed and the temperature might be directly proportional or it might be proportional in some kind of other thing like there might be that temperature is proportional to the log of the speed or the square of the speed. Ln 399. My questions is you can't figure that out per se, <u>but what I 'm really curious is if you think it really is directly proportional, so if you double the temperature do you double the speed? If you triple the temperature do you triple the speed? Is it directly proportional or is it less sensitive or more sensitive?</u> I'm thinking in terms of speed on		

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temperature.		
	Evaluated empirical consistency of the relationship between speed and temperature by examining incremental values of a quantitative model (graph of BZD). **Modified quantitative relationship** to now state that speed is "close to" directly proportional to temperature.	Ln 406. S1 Can we go back to 600? That's 51%. S2 This over here? What do you want me to do? S1 Can we go back to the 600, do we just click on this? S2 You can change it. (click) S1 9.4% and the other one was .51, so is that about? Is that what that's for? T Yeah that's actually not what that's for. Ln 419. S1 Oh okay. S2 Okay. We'll just look at this maximum point here is about. S1 400. S2 About 350-400. S1 Uh, huh. S2 And this one here. Okay what we're looking at is where the maximum points of these curves are. Ln 432. S1 Uh, huh. S2 And we can tell that this one is about 350 to 400. And this one here is about. Ln 437. S1 5,600? S2 About 600. And we know that this curve represents the 300 degrees and this one represents the 600 degrees, so if this was really 300 like about 300 and this one's really about 600. I would guess that they are directly proportional. I What do you think? S1 This one seems, we were saying before this one seems like it's more like 350 to 400. Ln 449. S2 Yeah. S1 So. S2 It seems a little bit more, yeah they're not directly. S1 Yeah they're not directly proportional. They're close though.

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Added information: T It turns out that the actual equation that governs this has to do with the fact that temperature is proportional to kinetic energy over all. The kinetic energy for a particle is, you may have seen this equation before, equal to one half me squared. So Ln 462. That's actually the thing that's governing this, except for the fact that you don't have a single molecule. You have a whole collection of them. So the proportionality is actually the temperature's actually proportional to the square of the velocity, so the velocity is actually proportional to the square root of the temperature. So it's really going up by around one and a half. It's a little hard to tell because of the curves, but that's how much it's.		
Summary: Ln 470. T Okay so we're going to leave this area. Just leave this for now, but the main take away thing though is as temperature goes up, energy goes up and that as temperature goes up molecules move faster but also heavier molecules move more slowly at a given temperature.		
Background information. Added information, field specific content:		

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Ln 480. T Okay so I need to explain what this thing is. So there's a property of a liquid called vapor pressure and where its comes from is if you have a closed container and I'm drawn to this box. And you have a liquid so there's some liquid in there. And Ln 483. There's nothing up here, what happens is some of the molecules of the liquid can escape into the gas phase and we end up with gas molecules. And so as time goes on more and more of these liquid molecules escaping into molecules of the gas phase and some of those gas molecules sometimes will go back into the liquid phase. So if you let the thing sit there for a long time and it's closed, eventually you'll reach a point when the number of molecules going into the gas phase is happening at the same speed as the molecules going into gas and back into the liquid Ln 493. Phase. At that point what happens is these gas molecules up here exert the pressure, just like any other gas, of any gas in a container will exert a pressure, so there's a pressure of this gas here, but it happens to be the gas that came from the liquid and we call that pressure vapor pressure. So vapor pressure for a liquid is somewhat of a measure of how volatile it is. Volatile		

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liquids that evaporate easily have high vapor pressures. Liquids that don't evaporate easily have low vapor pressures.		
Compilation of information phase. Showed vapor pressure simulation, selected variables and displayed the graph. Generation of a relationship between temperature and vapor pressure. Ln 499. So what we have is we have a simulation here where we can change what the liquid is and we can change what the temperature is and look at how vapor pressure changes with that. So what we're going to do is compare. Ln 505. T First of all we're going to worry about temperature but at the same time we're going to compare two different liquids: methanol, which has this shape, and ethanol, which has this shape. So they look the same with the main difference that they each have an OH group and a CH_3 group. The difference is that ethanol has an extra CH_3 group, so ethanol is a little longer. So go ahead on there and look at. you will examine both of them at the same time, but we want to first talk about temperature. So go ahead and do that. Look		

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at it and then I want you to come up with a description of how vapor pressures changes with temperature.		
	Compiled information from the vapor pressure (vp) simulation. **Selected two variables:** the compounds and the temperature. **Generated a semi quantitative relationship** that as temperature increased, vapor pressure increased by comparing the vapor pressure curves (quantitative models of vp) of methanol and ethanol at **incremental** temperatures.	S1 Okay. It seems like as temperature increases, pressure increases. S2 Okay and all right. Yeah, as pressure increases. I mean yeah, as temperature increases as we go across here, both ethanol and methanol show that their vapor pressures are increasing, so as temperature increases, pressure increases.

The majority of surveyed students in the primary case did not agree that, "This class would be more effective for me if the instructor provided the information and rules instead of asking me to gather information from the simulations in class and generate relationships myself." N=23, 32% agreed.

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Added content information. Ln 549. T It turns out that's true for all liquids, it's not just methanol, ethanol. That always happens for all liquids.		
Generation of a quantitative relationship		

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between vapor pressure and temperature. T Is it linear? Is temperature proportional? Is vapor pressure proportional to temperature directly?		
	Generated a quantitative relationship that vapor pressure is not directly proportional to temperature.	Ln 553. S1 It's not. It doesn't seem like it a straight for it to be linear it has to be more of a straight line. T Talk. S1 Oh, okay. For it to be linear it has to be more of like a straight. For it to be directly proportional. It doesn't seem like it's directly proportional because it's more of a curve. S2 Uh, huh. Yeah. Ln 564. S1 <u>And as it gets higher it increases faster, but here it's almost level.</u> S2: Yeah so it's not directly proportional. S1 But it is proportional. S2 Yes. T So you're saying? S2 It's not directly proportional.
Added information: Ln 576. T It turns out actually it's exponentially proportional. So the vapor pressure is proportional to ^{e}to some function of the temperature.		
Explanation: Ln 578. T Okay so come up with an explanation for why as temperature goes up vapor pressure goes up. So talk to each other about that. Remember what's happening, it's about liquid molecules escaping into the gas phase.		

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	Constructed an explanation for why as temperature increased, vapor pressure increased, because, according to the students, the increased heat causes the molecules to speed up, and they'd be running into the sides more and that would increase the pressure	Ln 583. S2 Well we know that at certain temperatures, a liquid becomes gas, so if at a standard temperature, there's a lot of liquid and you increase the temperature, it's going to become more gas, which causes not only the molecules to speed up, because of the increased heat, but since the molecules would be running into each other more, they'd be running into the sides more and that would increase the pressure. Ln 598. S2 Since we know that liquids turn to gases. S1 Uh, huh. S2 As temperature increases. The higher the temperature the more gas that would. S1 The more liquid that is turning to gas. S2 Yeah. The more liquid that is turning into gas as there's more gases floating around the more they run into each other the faster they move and the more they run into the. S1 The walls S2 To the walls. S1 Increasing pressure.
Comparison between evaporation and boiling: Ln 617. T Okay when you say that liquids turn into gases and this temperature goes up that happens more? Are you talking about boiling, when you say we know liquids turn to gas and that happens more with temperature. Are you talking about boiling or are you talking about something else? S1 Boiling. Ln 624. S2 If you want to		

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call it boiling. S1 Yeah. T I don't necessarily. I'm asking if that's what you were thinking about. If it's not that's fine. I'm just curious. S2 Yeah. S1 Uh, huh. I was thinking about boiling. Ln 635. T <u>Okay cause boiling always happens just at a single temperature. So like water, you heat it up it stays water until.</u>		
	Explanation: Attempted to explain the process of evaporation.	Ln 638. <u>S2 Okay well then actually if you leave</u>, <u>even if you leave your water bottle out and it's just sitting at room temperature, you notice that there's on the inside there's water that's forming.</u>
Comparison between evaporation and boiling: Ln 642. T Yes and actually where that's happening from is that's because some of it even at room temperatures where it has a vapor pressure so some of it can escape into the gas phase. Ln 646. S2 Uh, huh. T Which is a different thing than boiling. S2 Yeah. T Which is fine and I'm not being critical of what you said. It was fine. <u>It's more a matter I was trying to see if you were thinking in your mind of something boiling or you're thinking of something evaporating.</u>		

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Sounds like you were thinking of something evaporating.		
	Explanation: Attempted to explain the process of evaporation.	Ln 657. S2 Yeah but also if as the temperature increases, it's more likely to evaporate like if you left a glass of water outside on a day that's forty degrees, it would evaporate more slowly than a day that is eighty degrees.
Added information: Ln 662. T Correct. That's true and this plot kind of shows that. S1 Uh, huh. S2 Yeah.		
Comparison between evaporation at 40 degrees versus evaporation at 80 degrees. Ln 668. T So I guess my question is based on the way molecules move, based on what we saw earlier, why is that? So if they evaporate more quickly because the vapor pressure is higher and higher temperatures, but why is it higher and higher temperatures? What is it about the molecules at 80 degrees that makes them more likely to evaporate than at 40 degrees?		
	Explanation: Students attempted to construct a causal mechanism to explain what happens to molecules in a liquid as the temperature	Ln 674. S1 Okay I don't know, but maybe molecules expand at higher temperatures. S2 Umm. S1 Is that way off or? S2 I don't know if molecules are expanding as much as we know that the liquid itself would be expanding and I don't know what

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	increases. In the course of their construction, S stated that: -molecules expand at higher temperatures	the relationship between the liquid. S1 Maybe the molecules. Ln 687. S2 Between the liquid and the gas and the air and the flask is, but there has to be some type of relation.
Added information: Ln 690. T You can assume that there is no air in the flask. S1 Okay. S2 Okay. T The only gas in the flask came from the liquid.		
	Explanation: Students attempted to construct a causal mechanism to explain what happens to molecules in a liquid as the temperature increases. In the course of their construction, S stated that: -molecules expand at higher temperatures - molecules are weakened as the heat increases and they break apart.	Ln 698. S2 Okay, then we, I know that as temperature, increases the density or molecules spread out. S1 Why would it go into gas phase? What about the heat? What about the temperature and the pressure? S2 I'm not really sure why. What do you think? S1 It has to do, maybe because the molecules are weakened as the heat increases. Maybe they break apart. Ln 710. I What do you mean by weakened? S1 Weakened as in they're not held together as molecules well they're held together, but because they expand they're more easily breakable. Ln 716. I And what's expanding? S1 The molecule itself, but I don't know. S2 Until it breaks free as a gas. S1 Right, so. S2 As a single particle, not particle, but a single gas molecule in a flask.
	Analogy to ice	Ln 731. I So how do you envision

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	skating. Student postulated a hidden causal factor: some kind of a bond that seems to hold the liquid together in liquid phase. S1 suggested that it is an intramolecular bond that breaks, for example, the hydroxyl group will break off of ethanol when ethanol is heated, causing the molecule to go into gas phase. S2 remained uncertain but did suggest that there was something that would have to bond together to make it a liquid. Seemed to suggest an intermolecular bond: S2 See I guess I don't know what the difference is of what makes one thing a gas and how it becomes a liquid it would have something would have to bond together so that it would make a liquid as opposed to a gas. I'm not really sure.	it? S2 Well I'm going to draw another example to like let's say ice or anything else like you know how when an ice skater is skating on ice and you know how it leaves a little trail behind them on the thing. It's not because it's melting the ice it's because the actual. S1 The skate is slicing through. Ln 741. S2 The skate is heavy enough and it's a weak bond that's breaking it and it just turns into a little string of water and then it freezes right away again. Whereas what she's saying is the heat itself causes that bond in the liquid phase to break and then therefore becomes a gas. S1 A gas. T Did you say the bond in the liquid phase? S2 I'm not sure what's holding them together in the liquid phase or what makes it a liquid. Ln 753. T I'm curious as to what's, when you're envisioning this, what's being held together by this bond? Specifically. T Like something breaks, what's that, when you break the bottom up you're saying what's breaking? S1 The OH. I The OH breaks off? S1 From uh, huh. S2 They would all like ethanol as a gas one of those molecules just by itself would be a gas. Ln 773. I Your referring to what do you mean by molecule? Like the whole thing or a part? S2 The whole. The compound, the whole thing. If it was in a, like if it was up here in this part, just one of those would be in a gaseous phase as opposed to like when they're all together. See I guess I don't know what the difference is of what makes one

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		<u>thing a gas and how it becomes a liquid it would have something would have to bond together so that it would make a liquid as opposed to a gas. I'm not really sure.</u>
Summary: Ln 784. T Yeah don't worry about that just yet we're actually going to go into that direction a little bit, but I just wanted to make sure I understood what you just said. You're saying [referring to S2] that when it goes from a liquid to a gas it's like you have these two ethanol molecules near each other and now they're separate from each other. S2 Yes. T But the ethanol molecules in and of themselves remain intact by either case. Ln 795. S2 That's correct. Because ethanol it's like gas still. T So that's different from what you said [referring to S1] where the ethanol molecule itself breaks into two pieces? S1 Uh, huh. T So how do you feel about what he said?		
	Explanation: S1 and S2 disagree on the mechanism of evaporation.	Ln 806. S1 I think he could be right because I really wasn't sure. I was just hypothesizing. I And how do you feel about what S1 said? Ln 813. S2 Well I disagree because I think again I'm going to go back to the example of water is when it's in its liquid phase then it becomes steam which would be gas water, it's still water it's just

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		not really close together to making a liquid.
Explanation: Ln 820. T So that really is the way it's thought about [referring to S2 explanation]. That you have these individual molecules that are, something's causing them to stick together and don't worry about what that is just yet. <u>Something causes them to stick together and when they go into the liquid phase, when they go from liquid phase to the gaseous phase what happens is that molecules get pulled apart. That bond between one molecule and another molecule gets broken and they now can be pulled apart.</u> Ln 828. S1 Uh, huh. T And go into the gas phase.		
Explanation: T So now talk again and reiterate or iterate for the first time your idea as to why temperature going up causes that to happen more. So as temperature goes up you get more stuff in the gas phase. Why does that happen?		
	Explanation: Students attempted to re-explain their model. S1 now stated that the bonds between molecules were	Ln 843. S2 Okay. As we were saying before as energy or as heat increases. S1 Uh, huh. S2 There's more energy and the molecules themselves would be moving faster. S1 Uh, huh. S2 And if they're moving faster

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	weakening and breaking apart as opposed to before where S1 inferred that it was an intramolecular bond that was breaking apart when a liquid evaporated. S2 still appeared uncertain about intermolecular bonds and how they were involved in evaporation: S2 Yeah is it that, are all the molecules going to have just <u>broken bonds</u> on them that they could? I'm not sure. Actually I agree that there is something that has to be holding them together.	and they were really close together they couldn't move as fast yet the energy is still there. The heat's still increasing so therefore they would move apart, break apart whatever was holding them together as a liquid then they would be, have the energy to move apart and become a gas. That's why I think that as heat increases. Ln 859. S1 I think that's true but I think also that because the temperature increases it's also weakening the bonds and that would make it easier for them to try to move apart and break that bond. S2 Okay. I So is it weakening the bonds inside the? S1 Nope. I Molecule or between? S1 Between each bond. Ln 873. S2 You see this is what I don't understand is from what I understand of bonds there has to be. Where would that bond go just, what's happening? S1 It just breaks apart? S2 Yeah is it that, are all the molecules going to have just broken bonds on them that they. Ln 879. Could? I'm not sure. Actually, I agree that there is something that has to be holding them together and that is the heat would weaken the bond and since they want to be moving apart because of the heat they have the energy to move faster and they can't move fast together they have to move apart to turn into a gas whatever bond.
Summary of general mechanism of the process of evaporation:		

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Ln 886. T So you're saying that something's holding these things together, as temperature goes up the molecules are moving faster and as they're moving faster it's hard to hold them together so they break apart from each other. S1 That's right.		
Evaluation of empirical consistency of the relationship that as temperature increases, speed increases, by comparing two cases: ethanol and methanol. Ln 893. T You have a part of it as you have to break this bond and the energy makes the bond weaker. So thinking about that speed thing which, see if the speed idea, the faster the molecules move, the easier it is to break them apart. See if that makes sense with the trends between methanol and ethanol. So compare methanol and ethanol and see if that makes sense.		
	Evaluated empirical consistency of the relationship that as temperature increases, speed increases, by comparing two cases: ethanol and methanol. Uncertain about the variables	Ln 900. S1 That if the speed between them. S2 The speed. S1 That if the speed of one increases. S2 We don't have a list of speed on here. S1 Yeah. Should we go back to the other one?

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	to choose to evaluate these cases.	
Variables: Ln 910. T You don't actually need to because what you should do is you know the relationships between speed and temperature so if you look at one temperature what else would affect speed besides temperature?		
	Identified weight as a **variable**. **Compared** graphs (quantitative models of vp) for methanol and ethanol. **Explained** that because ethanol was heavier, the pressure wasn't increasing as fast as it was for methanol.	Ln 914. S2 Weight. T And you know what the two compounds are. S1 Uh, huh. S2 And we know that ethanol weighs more. S1 And that's why the pressure isn't increasing as fast as it is for the methanol. S2 That's right it [vapor pressure] would be increasing slower because. S1 Because ethanol is more heavy. Ln 929. S2 Because the speed isn't increasing as fast with the temperature and therefore (click). Well we know that speed and temperature are still related and. Ln 933. S1 That they're proportional to the kinetic energy. And that because the ethanol is more heavy, it weighs more. S2 Uh, huh. S1 And the pressure increases more slowly than it does for the methanol. S2 That's right. I Why would it increase more slowly? Ln 944. S2 Because it takes a lot more energy or it takes a higher amount of energy to increase the speed enough and the speed is

Phase of Guided Discovery Approach, the Activity structure, Guidance Strategy	Students' Learning Trajectory	Evidence: Student Discussion Triggered
		what we concluded. S1 Was the driving force behind. S2 What makes them break apart that them wanting to move faster makes them turn from a liquid to a gas or breaks the bond that holds them together as a liquid. Ln 954. S1 It takes a greater speed for the ethanol because of the fact that it's more heavy. S2 It's heavier. S1 And. S2 Would take more energy or a higher temperature to. S1 Or both. S2 Yeah to. S1 Break the bonds. S2 Break the bonds and. S1 S2 turn it into a gas.

Majority of surveyed students in the primary case (n=21) agreed with this statement, "Peer discussion is valuable for my understanding of science topics" with only 9% disagreeing.

Phase of Guided Discovery Approach, the Activity structure, Guidance Strategy	Students' Learning Trajectory	Evidence: Student Discussion Triggered
Modification of relationship: Ln 976. T Then what changes when molecular speed goes up to what you were saying?		
	Modified semi-quantitative relationship to include weight as a variable: As temperature increased, molecular speed increased, and vapor pressure increased. As	Ln 979. S1 We were talking about the weight. S2 So as temperature increases, molecular speed increases S1 And weight. S2 And weight. T Okay yeah, so I guess what I'm doing is little. S2 Vapor pressure increases. S1 Increases. T So as molecular weight goes up

Phase of Guided Discovery Approach, the Activity structure, Guidance Strategy	Students' Learning Trajectory	Evidence: Student Discussion Triggered
	molecular weight increased, vapor pressure would decrease.	then do the similar thing to this here as molecular weight goes up. S1 Temperature would still increase but would increase more slowly. T Yeah, but. S2 Well actually if the temperature stayed the same molecular speed would decrease, as molecular weight increased and vapor pressure would decrease also. T You agree? S1 Yeah.

Only 8% of surveyed students (n=24) disagreed with the statement, "I have had to modify some of my initial ideas about a chemical relationship by the conclusion of the lesson."

Phase of Guided Discovery Approach, the Activity structure, Guidance Strategy	Students' Learning Trajectory	Evidence: Student Discussion Triggered
Summary Ln 1008. T Okay so here molecular speed decreases and vapor pressure decreases. Okay good.		
Background information. Added information using field specific content. T Now, there's something else I just want to show you here before we go on to the next thing. These curves are actually used for identifying boiling points. What we really think of as boiling points and the boiling point is defined as the temperature at which this curve reaches 760. 760 is atmospheric pressure, so when the vapor pressure		

Phase of Guided Discovery Approach, the Activity structure, Guidance Strategy	Students' Learning Trajectory	Evidence: Student Discussion Triggered
reaches atmospheric pressure, that's when things boil, so let's go ahead and just look at what the boiling points are for these things and what we do is we just kind of back off down this curve until we reach 760. So for ethanol it's somewhere between 70 and 80 degrees. So ethanol's between 78 and 79 degrees. It's boiling point. So methanol is between 64 and 65 degrees.		
Generation of relationship between molecular weight and boiling point: T Does that make sense? So what do you think the relationship between molecular weight and boiling point is? Come up with just something like that. What's the relationship between boiling point and molecular weight?		
	Generated semi-quantitative relationship that as molecular weight increases, the boiling point also increases. **Confirmed** that as molecular weight increases with ethanol, the boiling point increased with information from the graph (quantitative model of vp).	Ln 1028. S1 As the molecular weight increases the boiling point also increases because for ethanol its more, it has a greater molecular weight and the temperature it takes for it to boil is between did he say 70 and 80? S2 Uh, huh. Something like that. Well we can check. T What are you doing? S1; S2 No we're just checking. T Oh, okay. S2 Yeah between 78 and 80 and so. <u>S1 As molecular weight increases, the boiling point increases.</u>

Phase of Guided Discovery Approach, the Activity structure, Guidance Strategy	Students' Learning Trajectory	Evidence: Student Discussion Triggered
		S2 That's right. S1 The boiling point is greater. S2 The boiling point is, yeah she's right.
[Explain] why as molecular weight increases, boiling point goes up?		
	Explanation: Students attempted to explain why the boiling point for ethanol was much higher than it was for methanol: -because there's more particles in ethanol? -because ethanol has a lower vapor pressure than methanol? -because ethanol is a heavier particle than methanol and therefore, it needs more energy to get it into the gas phase Using data from the graphs (quantitative models of vp) to support comparisons between the two substances.	Ln 1065. S2 That was the trend that we could see from the simulation. I Can you just re-articulate it? S1 Okay well as we moved the temperature from 70 degrees and 80 degrees the ethanol was between 150. I'm not sure what that stands for and then the Hg? T That's. S1 Okay. What we were basically looking at was where the temperature ended up for the boiling point for each of the compound. We saw that for ethanol it was much higher than it was for the methanol. Ln 1080. S2 And. S1 That's the trend. S2 See here with ethanol it's about 774.6 millimeters of mercury or torr or what have you and as [the teacher] said that when the vapor pressure equals the atmospheric pressure that's what the definition of a boiling point is, so when this boiling point, this boiling point is going to be larger than this boiling point just because there's more particles in it [ethanol]? Ln 1101. S1 [The teacher] wrote the rule on the board that we actually came up with that the vapor pressure decreases and it's. I: Yes go on. S1 I was just going to say that the vapor pressure for this one, for ethanol, is lower than this for the methanol. And that's part of the reason that the boiling point increases.

Phase of Guided Discovery Approach, the Activity structure, Guidance Strategy	Students' Learning Trajectory	Evidence: Student Discussion Triggered
		I But you mentioned something about particles. Ln 1114. S1 Well it would seem that the heavier a particle was or a molecule was the more energy needed to make it a gas in the first place and therefore the amount of energy needed to increase the pressure inside of this up to one atmosphere or 760 torr is going to be greater therefore the more heavier the weight the more particles or molecules or what have you the greater the temperature is needed to get the vapor pressure to equal atmospheric pressure. I [S1]do you agree or disagree? Ln 1124. S1 I agree with that. I agree.

71% surveyed students agreed with the statement, "I generally understand the relationships that other students generate and describe in this class" (n=24).

Phase of Guided Discovery Approach, the Activity structure, Guidance Strategy	Students' Learning Trajectory	Evidence: Student Discussion Triggered
Summary: T So as molecular weight goes up, vapor pressure goes down and therefore boiling point goes up. S1 Uh, huh.		
Added information about functional groups and alkyl groups. These were variables in the organic boiling points simulation. Ln 1126. T Okay so the next thing we then want to do is look at that trend that you said that the boiling point should go up as much		

Phase of Guided Discovery Approach, the Activity structure, Guidance Strategy	Students' Learning Trajectory	Evidence: Student Discussion Triggered
as the weight goes up. We're going to do that we the thing that just looks at boiling points. And before we do this I need to give you a hand out. Molecules are often thought of as a Ln 1130. carbon group and something else stuck to it and the carbon group is often called an alkyl group and so here's a number of alkyl groups and some of these alkyl; these are like the straight alkyl group, some of them are the same weight but different shape like the carbon's branch. So we have like for instance we have like purple here and there's another one that's on here called isopropyl which is the same kind of thing but it branches as opposed to being straight. It has the Ln 1139. same number of carbon and hydrogen, so in terms of weight they weigh the same, same number of atoms. So these are a bunch of different alkyl groups that we can vary in this and look at what happens to boiling point and then what's attached then is often called a functional group and so on here we have hydrogen. If Ln 1143. you have a hydrogen on there then these things are just alkanes and then we have fluorine, hydroxyl, which is an OH, kind of like we have on those ones there. The ones we just looked at chlorine, bromine, iodine and amine group, which is an NH_2		

Phase of Guided Discovery Approach, the Activity structure, Guidance Strategy	Students' Learning Trajectory	Evidence: Student Discussion Triggered
group.		
Gathered more information to evaluate the empirical consistency of the relationship that as molecular weight increases, the boiling point also increases with additional cases. Ln 1149. T So what we want to do is we want to start out we want to use this to see if your trend there actually works for more than say two compounds. <u>So the first thing to do would be to keep this as hydrogen and look at the relationship between molecular weight this will make a graph for you to the boiling point and molecular weight, then you vary how large this alkyl group is.</u> Ln 1154. How big the molecule is and it shows you a picture of the molecule as you go along. So go ahead and do that. You can hold onto this and see if it seems to, if your rule seems to hold.		
	Evaluated: Gathered information from the graph to **test** whether or not the boiling point increased with an increase in molecular weight could be **confirmed** for more than two compounds (empirical consistency). Compared data	Ln 1159. S2 (click) So as we go down here the boiling point does increase. (click)

Phase of Guided Discovery Approach, the Activity structure, Guidance Strategy	Students' Learning Trajectory	Evidence: Student Discussion Triggered
	points on graph using the bpt simulation (quantitative model of organic boiling points) and initially, confirmed the relationship.	
Variables: hydrogen was constant. Ln 1164. T Actually don't do those. Leave it as hydrogen for now.		
	Evaluated: Gathered more information keeping hydrogen **constant** as the functional group. **Compared** data points using the bpt simulation (quantitative model of organic boiling points) and **confirmed** that the boiling point increased with an increase in molecular weight for the cases they examined where hydrogen remained as the constant functional group (empirical consistency).	Ln 1166. S1 Uh, huh. S2 Yeah hydrogen. T Why don't you reset the graph? S2 (click) T Some of them don't move because they're the same number of part, so they have the same weight. So decide whether it not it works. S2 Yeah it works. S1 It does work. Ln 1181. S2 It works because as you come down the weight, as the weight increases the boiling point also increases.
Gathered more information to confirm relationship. **Designed a new test** with chlorine as the functional group. **Evaluation** of the relationship that as molecular weight increases, the boiling point also increases is empirically consistent across cases.		

Phase of Guided Discovery Approach, the Activity structure, Guidance Strategy	Students' Learning Trajectory	Evidence: Student Discussion Triggered
Ln 1186. T Okay. So that seems to confirm what you're are saying in terms of molecular weight and boiling point. So let's do the same thing again where instead of using hydrogen Ln 1188. we'll try something else instead. So let's try actually, let's try say chlorine for instance. So we'll have a chlorine on there and then the rest of it and so do the same thing. So reset the graph and then do the same thing using chlorine as the function group, just make sure it's not something special.		
	Gathered more information. Compared data points on graph using the bpt simulation (quantitative model of organic boiling points). **Evaluated empirical consistency of relationship. Confirmed** that as molecular weight increased, boiling point increased in cases where chlorine was the functional group.	Ln 1194. S2 (click) Yup. S1 It's still increasing but now the boiling points are much closer together. T Okay. S1 Before they were much. S2 With the trends exactly the same. T Okay, so. I Which is what? S2 Is that the trends are exactly the same as you can see that as you Ln 1211. S1 The molecular weight increases. S2 Increase the number of. S1 As molecular weight increases boiling point increases.
Designed a new test. Ln 1219. T Okay, so now what else could we do? What else should we study?		
	Designed a new test.	Ln 1221. S1 We could do another functional group to just to be sure,

Phase of Guided Discovery Approach, the Activity structure, Guidance Strategy	Students' Learning Trajectory	Evidence: Student Discussion Triggered
	Gathered more information with iodine as the functional group. **Compared** data points on graph using the bpt simulation (quantitative model of organic boiling points). **Confirmed relationship** that as molecular weight increased, the boiling point also increased with iodine as another functional group.	but we. S2 I don't think it would change anything. Ln 1230. S1 (click) S2 Exactly the same. S1 Exactly the same.

67% of students agreed with this statement, 4% disagreed n=21, "I find myself asking "what would happen if..." science questions more often in this course than other courses".

Phase of Guided Discovery Approach, the Activity structure, Guidance Strategy	Students' Learning Trajectory	Evidence: Student Discussion Triggered
Evaluation: The comparison. Ln 1236. T Oh, so just thinking back to what you had for chlorine how does that [referring to data where iodine is the functional group] look different than the chlorine one?		
	Evaluated the relationship by comparing the graph with iodine as a functional group and the graph with chlorine as a functional group using the bpt	Ln 1239. S1 It actually seems like they're moving over. T Okay. S1 On the graph because they're getting heavier and heavier to begin with because the functional groups are getting heavier and heavier as you move down.

Phase of Guided Discovery Approach, the Activity structure, Guidance Strategy	Students' Learning Trajectory	Evidence: Student Discussion Triggered
	simulation (quantitative model of organic boiling points).	
Evaluation of the empirical consistency of the relationship by designing a new test: Ln 1247. T Okay so what other study could you then do? S1 Umm. T So that's the chlorine line and the other one over there is the iodine line. S1 Uh, huh. S2 Yup.		
	Evaluated relationship by suggesting another test with another functional group.	Ln 1258. S1 We could try it without a functional group at all and you'd have to have one.
Evaluation: **Design a new test** where the functional groups change now and the alkyl chain stays the same. Ln 1261. T That's a good idea and actually that's the way people think about it. That's what hydrogen is, hydrogen is actually not a real functional group. S1 Oh, okay. T Well what about leaving one alkyl group and changing the function groups and see what happens then? See if it works when you just change alkyl groups. Actually why don't you choose a longer one? Ln 1271. S2 Oh, okay. S1 Reset that? T Yeah.		

Phase of Guided Discovery Approach, the Activity structure, Guidance Strategy	**Students' Learning Trajectory**	**Evidence: Student Discussion Triggered**
S1 Okay. (click)		
	Changed variables. Gathered information. Compared data points using the bpt simulation (quantitative model of organic boiling points) **Encountered discrepant information. Expressed surprise** when they discovered that as molecular weight increases, the boiling point does not increase. Methyl hydroxide, even though it had a similar weight to other compounds, did not follow their trend; that is, methyl hydroxide boiled high for its weight even though it was lighter than methyl chloride.	Ln 1278. S2 <u>Why does this thing appear?</u> S1 Do you need that? Hydroxyl. S2 Hydroxyl. S1 The OH. I What are you looking at now? S1 The hydroxyl, well we'll see that. <u>S2 It's the only one that's not in.</u> <u>S1 In the line. It's not linear.</u> It's sort of higher. S2 Yeah, it's. I Hydroxyl? S1 Uh, huh. Ln 1300. S2 <u>It stands out. For some reason.</u> S1 <u>It doesn't follow the trend.</u> S2 <u>It doesn't follow the trend.</u> Ln 1318. S1 It boils high for its weight because chlorine boils lower and that's much, that's heavier.
Gathered more information. **Designed a new test:** Ln 1321. T <u>Okay so the way to confirm that something that has to do with the OH?</u>		
	Designed a new test with ethyl as the alkyl group to **evaluate the empirical consistency** of relationship with additional cases with	Ln 1324. S1 <u>We could try another alkyl group. See if it follows the same trends.</u> S2 Yeah we could. S1 So I guess let's try something light like ethyl. S2 Yup. S1 Uh, huh.

Phase of Guided Discovery Approach, the Activity structure, Guidance Strategy	Students' Learning Trajectory	Evidence: Student Discussion Triggered
	hydroxyl groups **Gathered more information.** **Compared** data points on graph using the bpt simulation (quantitative model of organic boiling points). **Confirmed** that the trend is empirically consistent despite the length of the alkyl chain: those compounds with hydroxyl groups tend to boil at a higher bpt compared with other compounds that weigh more. Pointed out the amine group.	S2 Yeah it does. S1 It still does the same thing. S2 Yeah. Ln 1345. S2 <u>The hydroxyl still boils at a higher rate it doesn't follow the same trend as the other.</u> S1 These others increase almost linearly. Almost in a line, but hydroxyl's kind of out, at it's own boiling point. S2 Hydroxyl's right here and it's. S1 Right it's far away. S2 Abnormally high. Ln 1357. S1 It's abnormally high because chlorine which is heavier than hydroxyl is- it boils at a lower boiling point that hydroxyl does. Ln 1360. T It looks like the, S1 Is that amine? S2 You mean? S1 The blue one [referring to ethyl amide data point on the graph]?

75% of surveyed students (n= 24) agreed and 4% disagreed that, "The use of simulations in class has contributed to the development of my ability to critically analyze a problem in chemistry."

Phase of Guided Discovery Approach, the Activity structure, Guidance Strategy	Students' Learning Trajectory	Evidence: Student Discussion Triggered
	Explanation: Students attempted to explain the anomaly by looking for what makes hydroxyl and amine different from the other functional groups. They suggested that hydroxyl and amine were compounds and not elements and that hydroxyl was negatively charged.	Ln 1369. S2 And as we can see from this right here is that both of them [hydroxyl and amine] are not elements, they're compounds. S1 Uh, huh. This one has the negative one charge OH.

Phase of Guided Discovery Approach, the Activity structure, Guidance Strategy	Students' Learning Trajectory	Evidence: Student Discussion Triggered
Added information: Ln 1373. T <u>Actually neither of them [hydroxyl and amine] are really charged. OH is in water. This is hydroxyl and this is not charged. But you're right they are groups of atoms as opposed to single atoms.</u>		
Modification of initial relationship that as molecular weight increases, the boiling point increases: Ln 1375. T Okay, so can you modify this rule here in some way?		
	Students attempted to modify the relationship in light of the new information. Referring to the bpt simulation (quantitative model of organic boiling points),they responded that, "as molecular weight increased boiling point increased up to a certain point and then it decreased again." S2 appeared to express some dissatisfaction with this modification of the initial relationship.	Ln 1384. S1 I guess well, we could say that like if this was our line instead of just points. If this was an actual curve we could say that hydroxyl was the peak. Like it was the peak boiling point for the group that we were looking at, so we could say that as molecular weight increases boiling point increases up to a certain point and then it decreases again. And then it follows the chart. See what I'm saying? Ln 1391. S2 It would have two peaks though! And these aren't. Let's see. These are in a specific.
	Students encounter **discrepant information** again. Students **predicted**	Ln 1394. S1 Why is amino over here? (click) I think it should be this way. Over here somewhere [pointing to bpt graph on the

Phase of Guided Discovery Approach, the Activity structure, Guidance Strategy	Students' Learning Trajectory	Evidence: Student Discussion Triggered
	that if amino groups followed the trend that as molecular weight increased, boiling point decreased, it should have been in a different position on the graph of the bpt simulation (quantitative model of organic boiling points).	simulation]. I Why do you think it should be over there somewhere? S1 Well because it's heavier than iodine and iodine is here, so it just seems like. If it was supposed to follow that trend it would be over there. Ln 1403. S2 Your right that wouldn't be, S1 It's over here.
Consider other **variables:** Ln 1406. T So let me ask this a different way. I think that might have been too open-ended. So right there you're saying boiling point depends on molecular weight and nothing to do with what the molecule is, just how heavy it is. For lots and lots of things that seems to work, but now it looks like there were things that have the same molecular weights, but have very different boiling points. So boiling point depends on what then?		
	Explanation: Students sought other factors to explain the anomaly. S2 postulated a hidden causal factor of an intermolecular bond between two hydroxyl groups.	Ln 1414. S2 Do you mind if I draw or? T No you can draw there. S2 Okay. Wouldn't the, on this one say, remember how we were talking about how there would have to be a bond between things in a liquid to hold them together as a liquid? S1 Uh, huh. S2 What do you think about the bond, what kind of bond there would be between two hydroxyls. Ln 1429. S1 Two hydroxyls? S2 Would it be a stronger bond

Phase of Guided Discovery Approach, the Activity structure, Guidance Strategy	Students' Learning Trajectory	Evidence: Student Discussion Triggered
		than say between two chlorides or two bromides? S1 Most likely because, between two hydroxyl groups? Between and OH and an OH? S2 Like between an OH and an OH. S1 Well you could always.

71% agreed with this statement and 10% disagreed with "I modify my ideas about chemistry more often because of classroom discussion than from doing homework" (n=21).

Phase of Guided Discovery Approach, the Activity structure, Guidance Strategy	Students' Learning Trajectory	Evidence: Student Discussion Triggered
Added information: Ln 1441. T So they stick together a lot and therefore the bonds between the molecules are called the intermolecular forces. They are unusually strong that the OH groups and because of that they tend to have higher boiling points.		
Prediction of vapor pressures of compounds with hydroxyl groups T And do you think they [compounds with hydroxyl groups] have higher vapor pressure or lower vapor pressure?		
	Predicted that compounds with hydroxyl groups will have lower vapor pressures (than compounds without hydroxyl groups).	S1 Lower vapor pressure.
Designed a new test that made a comparison between compounds with hydroxyl groups with those compounds of a relatively		

Phase of Guided Discovery Approach, the Activity structure, Guidance Strategy	Students' Learning Trajectory	Evidence: Student Discussion Triggered
high molecular weight. Ln 1449. T Okay, so the next thing we want to do then is we want to go back and check. Do a test of that modification to your rule and so we're going to go back to the vapor pressure molecule we looked at before. And what we want to do is we want to look at two compounds. One we want to took at water and the other one we want to look at is called benzene. Ln 1454. So we're not going to do that yet, but I want to show you what, so water. You know what water looks like. Water has a molecular weight of 18. This is benzene so it's a flat ring and so it doesn't need OH's or anything like that. It has a molecular weight of 78. So for your original rule of just molecular weight, which of these would have a higher vapor pressure – water or? Ln 1461. S1; S2 Benzene. T Or benzene. T For your original [relationship], would it have a higher vapor pressure or lower vapor pressure?		
	Based on the original relationship that as molecular weight increased, boiling point decreased, students stated that they originally would have predicted that benzene would have	Ln 1468. S2 For our initial, <u>oh, the lower vapor pressure because we would have said that it weighs more than water.</u>

Phase of Guided Discovery Approach, the Activity structure, Guidance Strategy	Students' Learning Trajectory	Evidence: Student Discussion Triggered
	had a lower vapor pressure than water because it weighed more than water.	
Prediction based on evidence of hydrogen bonding. Ln 1471. T Okay. So then so you think that this [pointing to water] weighs less so it [water] probably has a higher vapor pressure. So my question then is because of the OH thing, could this [pointing to water] have a higher vapor pressure than that [pointing to benzene]? T Okay, so my question is could this [water] possibly have a higher vapor pressure than that [benzene]?		
	Students **predicted** that in light of the new information, water could have a higher vapor pressure than benzene because of H bonding, but if H bonding was not a factor, then students predicted that benzene would have had the lower vapor pressure because it weighed more than water.	Ln 1488. S1 It's possible. S2 It is. T Okay. Do you know that this would have a higher vapor pressure than that? S1 No. T So it might, but it might not. And if the hydrogen-bonding thing wasn't in play then could this have a higher vapor pressure than this? Ln 1500. S1 Yes. S2 If the hydrogen bonding was not in play? T Right. S2 Then this [pointing to benzene] could not have a higher vapor pressure than that [pointing to water]. I Why? Ln 1510. S2 <u>Because this [pointing to benzene] weighs more</u>

Phase of Guided Discovery Approach, the Activity structure, Guidance Strategy	Students' Learning Trajectory	Evidence: Student Discussion Triggered
		and until we had figured out the bond thing, we figured that everything that weighed more had lower vapor pressure.
	Compiled information on vapor pressures of benzene and water using the vapor pressure simulation. Compared vapor pressures and stated that benzene has a greater vapor pressure [than water].	S1 Benzene is greater than water.
Comparison: Ln 1540. T Okay so which one has the stronger of the bonds between molecules – benzene or water?		
	Explain: Compared bonding in benzene with the bonding in water to explain differences in vapor pressure between the two substances on graphs (quantitative models of vapor pressure). Articulated a causal relationship using the variables: energy, heat, bonds, vapor pressure, temperature, and , boiling points. Predicted that water would have a higher boiling point because it has stronger bonds than benzene. Identified a causal factor, bonding, as being more	Ln 1543. S2 Water. S1 Water has the stronger bonds. I And how can you tell? S2 Because the pressure. S1 Of benzene is higher than the pressure of water. S2 And therefore it would take less energy for. Ln 1557. S2 The pressure in there [pointing to animation of flask containing substances] to reach atmospheric pressure or boil. Ln 1562. S2 Less energy, less heat to break the bonds of benzene because the pressure at a given temperature is higher than that of water. Ln 1566. T So which has a higher boiling point? S1; S2 Water. S2 Water would have a higher boiling point.

Phase of Guided Discovery Approach, the Activity structure, Guidance Strategy	Students' Learning Trajectory	Evidence: Student Discussion Triggered
	important than the factor of weight in determining vapor pressures and boiling points.	

9.52% of surveyed students agreed and 71% disagreed with the statement, "Chemistry is too abstract to understand deeply" (n=21).

Phase of Guided Discovery Approach, the Activity structure, Guidance Strategy	Students' Learning Trajectory	Evidence: Student Discussion Triggered
Added information and summary: Ln 1581. T I need to clear up a couple things for them just give them some language so that you can, these things are called intermolecular forces and the idea is that the stuff you came up with speed is actually really not it. It really is just these forces and what happens is bigger molecules tend to have stronger forces than littler molecules did. But when you have, but there are other things aside from size Ln 1587. that led to changes in the strength of those forces. So bigger molecules, size influences the strength of the forces, universally always bigger as far as forces, but there are certain groups that lead to ultra strong forces.		

4.13.3 Learning outcomes

For this pair of students, the transcript evidence suggested that the students were engaged in multiple inquiry processes in response to GD instruction. For example, the student pair was observed generating a semi-quantitative relationship that as temperature increased, molecular speed increased by spontaneously comparing quantitative models of BZD at two extreme temperatures (Ln 57-104); evaluating the empirical consistency of the relationship for all molecules at that speed based on a teacher question to evaluate (Ln 104-Ln 121), and modifying their initial relationship to suggest that there is a distribution of speeds (Ln 121-126). Students were further observed generating an explanatory model based on a why question from the teacher (Ln 138- 192), and modifying the original relationship to include pressure as a variable (Ln 204-236) based on problem solving strategies proposed by the teacher (Ln 199, Ln 210).

Students learning pathways also included the processes of generating a quantitative relationship (based on a teacher question (Ln 338), that speed is proportional to temperature and speed is inversely proportional with the Chemland graphs (quantitative model of BZD); evaluating the empirical consistency of the relationship between speed and temperature by examining incremental values of a quantitative model (Ln 406-449) based on a teacher directive (Ln 394), and modifying the quantitative relationship to now state that speed is "close to" directly proportional to temperature (Ln 449).

In addition, students encountered discrepant information with Chemland later on in their learning pathway, and expressed surprise when they discovered that as molecular weight increases, the boiling point does not increase (Ln 1278-1318) in all cases. Methyl hydroxide, even though it had a similar weight to other compounds, did not follow the trend they had originally generated; that is, methyl hydroxide boiled high for its weight even though it was lighter than methyl chloride. Students were observed designing a new test based on a teacher question to confirm the finding (Ln 1321). Students spontaneously selected ethyl as the alkyl group to evaluate the empirical consistency of the hydroxyl group anomaly (Ln 1324). Students gathered more information with Chemland and compared data points on graph using the boiling points simulation (Ln 1324-1345). Students confirmed that the trend was empirically consistent despite the length of the alkyl chain: those compounds with hydroxyl groups tended to boil at a higher temperature compared with other compounds that weighed more (Ln 1345).

Students learning trajectories also showed evidence of the student pair constructing explanatory models to explain what happened to molecules in a liquid as the temperature increased. In the process of their construction, the student pair used an analogy to ice skating to explain that molecules expand at higher temperatures and molecules are weakened as the heat increases and they break apart (Ln 741). The students were observed postulating a hidden causal factor: some kind of a bond that seems to hold the liquid together in liquid phase (Ln 1429), and eventually used this hidden factor to articulate a multivariate, causal relationship between energy, heat, bonds, vapor pressure, temperature, and boiling points (Ln 15150-1562). The student pair predicted that water would have a higher boiling point than benzene because it has stronger hydrogen bonds than benzene (Ln 1562), based on a teacher activity. The student prediction and explanation (Ln 1543) indicated that students were able to weigh the causal factor, hydrogen bonding, as being more important than the factor of weight in determining vapor pressures and boiling points.

Taken cumulatively, this learning trajectory may be considered sophisticated for introductory chemistry students, suggesting that the GD approach to instruction in the primary case is capable of eliciting more complex scientific processes about chemistry during instruction.

Sample excerpts of other learning episodes. Below are highlights of learning episodes from the other in-depth pair sessions.

An analogy. From in-depth pair session 1, was an example of students using an analogy to explain molecular motion:

> Ln 455. S1 Well it's the same if you have like a group of people, okay like sumo wrestlers yeah.
> I Sumo wrestlers.
> S1 They are very slow because they have a large mass, where as I don't know like marathon runners. Okay they tend to be very slow and then fast (garbled). It's like that's how they are. (laughter)
> S2 Yeah exactly.
> I All right.
> T When a marathon runner runs or when sumo wrestler runs are they expending the same amount of energy or not given that they are running at different speeds? Like you said.
> S1 Umm.
> T In a real sense. (laughter)
> S2 Ahh.
> S1 Unnno.
> S2 Well I mean the marathon runner doesn't have to use as much energy to move himself.
> S1 Yeah.
> S2 As the sumo wrestler, so.
> T But what about the fact that the marathon runner is running faster?
> S2 Ahh.
> S1 Well okay then if the marathon runner was running faster then he be giving off more energy as he runs, whereas the vise versa for the sumo wrestler.
> T So the sumo wrestler.
> S1 The sumo wrestler may be trying harder, but he's not letting off as much energy cause he has a greater mass.
> Ln 530. S2 As the mass of a molecule goes up, it's harder…it takes more energy for it to move faster, so it doesn't go as fast at the same temperature.

Coordinating data with theory. From in-depth pair session 1, the student pair encountered disconfirming information and attempted to coordinate this new information with their theories on molecules.

S2: Yeah I mean…the amine and the hydroxyl ones seem somewhat. Oh according to the graph it looks like they…all three of those should have the same molecular weight, but the boiling points are all different.
T: They do.
S2: If I'm reading them…Yeah okay.
T: They do, close to it. So can you point to the ones that your thinking or.
S2: These two right here.
T: Okay.
I: So you're wondering about why they are over there?
S2: Yeah, if they have the same molecular weight, I would think they would have the same boiling points.
Ln 1073. T: So come up with an explanation for why when you have an OH there or we have an NH_2 there, you get anomalously high boiling points.
S2: Umm.
I: Can you really say what you're thinking?
S2: I keep forgetting there. Sorry. (laugh)
S1: We need a periodic table here somewhere.
I: A periodic table? Tell me why you're looking at the periodic table.
S1: Because I'm looking for electronegativity. For the trend of electro negativity cause hydroxyl would be right there and has the OH group and since O has a greater electronegativity, so it would pull electrons more towards the end so it won't bond wise…so like the bonds between C and H would be weaker then …correct? Because electrons would be spending more time over by the OH group. I don't know.
I: And how would that effect boiling point?
S1: Because then it would go into a gas phase sooner and reach the 760.
I: Because?
S1: Because it would be traveling faster…since the bonds are weaker molecules tend to travel faster than skipping to a gas phase and like break a part kind of like.
I: Than if they were stronger, they would do what?
S1: They would stay as a liquid longer or they travel slower. That's how.
T: Which one are you saying does have the stronger bonds?
S1: Ah.
T: With the OH or without the OH.
S1: Without the OH.
S2: Right.
I: And why do you think without the OH there's a stronger bond?
S1: Because of electronegativity, if that makes any sense.
Ln 1122. T: Work back from the data, so start with…you're doing one way which is fine, but try doing it the other way.
S1: Okay.
T: Start with we think the OH has high boiling points therefore.
S1: Everything I just said really make sense cause okay four of them have electronegativity [greater] than O.
I: Can you speak up loud?
S1: Wait because I just contradicted myself (laugh).
I: That's okay.
S1: Fluorine has a greater electronegativity than O and so, but it like still follows the trend for like…for the data.

<u>**Multi-variate relationship construction.**</u> Students from in-depth pair session 3 constructed a multi-variate quantitative relationship between mass, energy, distance, and force after working with the BZD simulation in the excerpt below:

> Ln 211 S2: I think basically it's like…I'm trying to draw a correlation between the temperature and the molecular size. <u>But it comes down to basic physics.</u> You have a given force. In this case temperature is not variable so therefore a change in the amount of mass. So it's a given force acted on a changing mass and the larger the mass the less slower it's going to be, the smaller the movement.
> Ln 224. S2: I think I'm thinking of this really as far as like mass. You have like a mass, or a <u>force is something like a given mass acted on by a force equals the certain distance or change in the position of the mass.</u>
> T: Okay it's like how much, you're saying like how well you can change the position of the mass.
> S2: Yeah.
> T: If it's a bigger mass it will change more or it will change less?
> S2: <u>No if it's a bigger mass and the force stays the same as compared to the smaller mass it's going to move less.</u>
> T: Okay. What in what we've been doing…what equates to the force?
> <u>S2: Energy or heat temperature.</u>
> T: Okay <u>so if the temperature is exerting in some sense this force that's</u> making the molecules move and <u>at a given temperature</u>.
> Ln 245 S2: Well yeah. It depends on what you're varying. If you vary the temperature or if you vary the molecular size. As you vary molecular size the greater the molecular size the greater the mass with same temperature acting upon it you're going to get less and less movement. Whereas if you have greater temperature on a given mass you're going to get more movement.
> T: Okay so discuss this for a second. So the thing you just here where you has one temperature and you looked at different molecules was the force changing between those?
> S2: Well force is the energy. No it doesn't.
> S1: <u>It's constant here.</u>
> S2: Yeah the variable in that case is mass. I forget the equation for force. It's like.
> S1: <u>Yeah the only thing that is changing is mass. You can't compare temperature right now.</u>
> Ln 276 S2: Well I was just saying a force to me. I mean this could be completely wrong. It's close but it's not…<u>I mean force to me is like something that's acting on something else.</u>
> S1: <u>Right and that would be the temperature here.</u>
> Ln 290 S2: [Temperature energy heat] is acting on the molecules. Molecules because in this case xenon is the larger molecule that force is hitting it but the xenon's not moving a lot because it's so large and dense where as the helium. <u>The much lighter mass is acted on upon by the same amount of energy, the same magnitude force; you get a greater displacement.</u>
> Ln 309 T: So you're actually…what you're actually doing <u>is you're coming up with an equation in broad strokes</u> that defines particle motion, motions of particles.

Postulating a hidden causal factor. Students from in-depth pair session 6 postulated a hidden causal factor to explain discrepant information.

S1: Weight doesn't seem to have a correlation here, because the fluorine weighs the most and it's on the bottom, which goes against what we thought before, or I thought before. OH is in the middle, yet it's on top, and our NH_2, which weighs the least, and which I figured would be on the bottom, is in the middle.
Ln 1660 T: Why is it that something with an OH-and why is it that this kind of interaction might lead to that?
S2: Um. If you have an-I guess if you have an attraction between molecules that needs to be overcome for them to break apart and go into-become-go into [garbled] and so that takes more energy to do that than just to get them going.

More complex processes. Thus, in addition to student engagement with some fundamental processes commonly associated with scientific inquiry, some of the learning outcomes appeared to also include student engagement with coordinating theory with data, using analogies to support explanatory models, postulating hidden causal factors, and constructing quantitative relationships. For an introductory level course in chemistry, these outcomes may represent student engagement with more complex processes associated with scientific inquiry.

4.13.4 Conceptual understanding

In addition, all student participants (n=12; 6 student pairs) in the in-depth pair sessions completed an individual pre and post test for conceptual understanding. At the culmination of the GD approach to instruction in the in-depth pair sessions, significant pre-post gains emerged on the test for conceptual understanding (paired t test, $p<0.01$) for in-depth pair session participants.

At the end of the course, the surveyed students from the primary case reported on their learning outcomes at the end of the semester of instruction:

1. 91% of surveyed students in the primary case agreed that, "Having us generate, evaluate, and modify relationships in class is valuable for my understanding of the concepts in chemistry" with 9% neutral (n=23).

2. The majority of students (n=21) in the primary case agreed with this statement: "I understand how scientists assess and modify theories about unobservable processes."

3. The majority of students (n=21) in the primary case agreed with this statement: "By the conclusion of class, I usually feel I understand the chemistry concept of that lesson".

These preliminary test findings with a very small sample size and classroom CAT survey findings suggest that the GD approach to instruction may have facilitated conceptual learning outcomes in addition to the process outcomes.

4.13.5 The hypothetical role of the computer and implications for use

In every in-depth pair session, spontaneous (not teacher-directed) instances of students selecting and reselecting variables, pointing to color-coded curves on the graph and comparing curves, and pushing values to their extremes with the interactive computer tools were observed. Spontaneous student use of Chemland suggested that student use of the software may have played a hypothetical role in facilitating student learning during instruction. This section attempts to explore the implications of students working with Chemland during the GD approach to instruction.

Implications for generalizability. It is plausible that being able to process large amounts of information and to view the information in multiple representations may have had some implications for pattern generation and generalizability.

1. 90% of students agreed that, "An important advantage of the computer simulations is that they make unobservable processes in chemistry more explicit to me" (n=21).

2. 76% agreed, 5% disagreed that, "The computer graphics of molecular structures used in lecture contributed to my learning in this course in a way that went beyond what I learned from the pictures used in the text" (n=21).

Surveyed students confirmed that they had no difficulty in seeing patterns in the data from Chemland:

3. 71% of students reported no difficulty in seeing patterns in the data from the computer simulations from the survey statement: "I find it difficult to see the patterns in the data from the computer simulations" where 71% of students disagreed with this statement, 21% of students were neutral (n=24).

4. And that it was not difficult to determine what the important information was in the computer simulation, according to the survey statement, "It is difficult to determine what the important information is in the in-class computer simulations" where 12% agreed 67% disagreed (n=24).

Thus, working with Chemland may have had some implications for pattern generation.

Implications for evaluation. It is hypothesized that selecting and reselecting variables and values and comparing curves on a graph may have had some implications for evaluating the consistency of the relationship across cases. In addition, pushing the values to their extremes with the use of the interactive computer tool may have afforded what if scenarios that helped students evaluate the consistency of the relationship across cases:

5. 67% of students agreed, 4% disagreed (n=21) with this statement, "I find myself asking “what would happen if...” science questions more often in this course than other courses".

6. “I sometimes input extreme case data in the simulations to test the boundaries of my ideas about chemistry”: 67% agreed, 25% neutral (n=24).

Students were also observed designing new tests by selecting different variables and controlling for others with the computer, and this may have had some implications for evaluating the consistency of the relationship. Thus, working with Chemland may have had implications for hypothesis evaluation and modification.

Survey outcomes on computers. Surveyed students in the primary case reported the following about working with the computer simulations in class:

1. The majority of surveyed students in the primary case selected that, "In general, I am able to complete __80-100___% of the activities or exercises called for with the computer in chemistry".

2. 75% of surveyed students (n= 24) agreed and 4% disagreed that in the primary case, "The use of simulations in class has contributed to the development of my ability to critically analyze a problem in chemistry."

Students in the primary case reported, however, that teacher guidance was necessary for the effective use of the simulations:

3. 76% of surveyed students (n=21) in the primary case agreed with the statement that that, "Teacher guidance is necessary for the effective use of the simulations."

4. A majority of surveyed students (n=24) ranked the independent use of simulations outside of class as one of their bottom three choices out of nine choices to "rank where the greatest learning happens for you in chemistry."

5. Independent use of simulations outside of class and reading the text were ranked in the bottom three experiences for students in the primary case out of nine choices.

Thus, the CAT post-survey items on computers appeared to suggest that computers, in addition with teacher guidance with the computers, played an integral role in students' learning according to the surveyed students. It was hypothesized that these activities with Chemland may have had implications for student pattern generation and hypothesis evaluation and modification, as well as for the number of cycles of pattern generation and evaluation of the consistency of relationships that students could go through in the GD approach to instruction.

4.14 A retrospective analysis of process test results

An initial test in 1999. In an effort to home in on those college science classrooms that are effective at fostering inquiry processes in the classroom, an initial test was created in 1999 (Rea-Ramirez & Stillings, 2000) and administered to several introductory science classes, including the primary case, lecture 1 and lecture 2 classes. The test was administered to these three classes in 1999 at the beginning of the semester of course instruction (pre-test) and at the end of the semester of course instruction (post-test).

There were 5 open-ended essay questions developed, piloted, and administered, two of which are relevant here.

The first question was designed to assess students' ability to generate hypotheses: "Two people are sitting in a room at equal distances from a bottle of perfume. After the bottle is opened, one person smells the perfume and the other person does not." The directions were to write a list of questions that occur to you about the statement, and based on one of these questions, write a well-formulated hypothesis that could actually be investigated.

The second question was designed to gauge how students could describe data and analyze a relationship: "A farmer wanted to compare two corn varieties and their responses to varying amounts of water. She believed that Hybrid B would produce a better yield than Hybrid A, and she believed that daily watering would increase yields. She planted her north field with Hybrid A and her south field with Hybrid B. She watered one half of each field daily, while the other half of each field was watered once every four days." The data (in bushels per acre of corn) were displayed as a table and a graph. Students were asked to: describe the data without drawing any conclusions, to evaluate the farmer's hypotheses that hybrid B would produce a better yield than hybrid A and that daily watering would improve yield, and to identify the assumptions the farmer made in the experiment, and to answer what further experiment might help to evaluate the two hybrids and the effects of watering. Both questions appeared in the same form on the pre test and the post test.

The pre and post tests were collected at the end of the course term (n=198 pre tests and 198 post tests) from the primary case, lecture 1, and lecture 2; blinded and scored with two coders who maintained an inter-rater reliability of 90%. The scores indicated that students from the primary case, lecture 1, and lecture 2 had similar marks on the pre-test (Rea-Ramirez & Stillings, 2000).

But by the end of class instruction in 1999, only one class emerged with significant improvements on the test. Students who attended the primary case performed significantly better on the test questions designed to measure the process skills of generating hypotheses, describing data, identifying assumptions behind conclusions, and designing experiments (positive pre-post differences $p<0.05$) than students who had been in lecture 1 or lecture 2 that year (Rea-Ramirez et. al., 2000).

Even though this was an initial test administered in 1999, a year prior to the current study, these initial findings suggested to us that learning of process skills may have occurred in the primary case. In order to best explain how learning may have occurred in the primary case the year the test was taken, the current study on the primary case and lectures 1 and 2 provided us with an in-depth examination of instruction in these classes. In a retrospective analysis, this section attempts to support the hypothesis that the reason that students in the primary case did better after course instruction than in the lecture classes in 1999 was because of the GD approach to instruction in the primary case that triggered and sustained student engagement with fundamental processes of science, the same processes that were tested for.

Pre-post course gains within the primary case. There were three regularities within the primary case from 1999, the year the test was taken to the following year, the year of the current study. The three regularities in both years were:

1. The primary case course was taught by the same teacher in both years.
2. The primary case teacher was documented as employing the GD approach to instruction in both years (Khan, 2001; Khan 2002).
3. The admission requirements for students enrolling in the primary case did not change in either year.

Thus, the GD approach to instruction within the primary case was similar in both years and the student sample in the primary case was drawn from the same population in both years.

I discovered from the current study that the GD approach to instruction appeared to trigger and sustain student engagement with some fundamental and complex inquiry processes during instruction in the current study, so it is reasonable to suggest that since there were a number of important regularities in both years, a similar finding may apply to the primary case in 1999. That is, the GD approach to instruction may have triggered and sustained student engagement with fundamental and complex inquiry processes in both years of the primary case.

Furthermore, the process skills that students in the primary case performed significantly better on at the end of course instruction on the initial test were the same processes that we observed in the current study on the primary case. That is, students from the initial course performed significantly better after course instruction on the test questions designed to measure the process skills of generating hypotheses, describing data, identifying assumptions behind conclusions, and designing experiments (positive pre-post gains, $p<0.05$), and these were documented as the same processes we observed in the current study on the primary case. Thus, a viable hypothesis that could possibly explain the significant improvement in process skills after course instruction on the initial test was that sustained student engagement with these processes in the primary case contributed to the statistically significant pre-post gains on the initial test.

Primary case performs better than the lecture classes. Like the primary case, the lecture classes (lecture 1 and lecture 2) also completed the initial test in 1999. In addition to the regularities within the primary case listed above, there were four non-statistical and statistical regularities that persisted in the lecture classes in both years:

1. There were no significant differences on the pre-test between the primary case, lecture 1, and lecture 2.

2. The lecture instructors did not change from year to year.

3. The lecture instructors taught in the same way from year to year.

4. The admission requirements for the lecture class did not change in both years.

The current study discovered that there were observable differences between the GD approach to instruction in the primary case and the approaches to instruction that were observed in the lecture classes. Since the primary case did not change instructional approaches from year to year and the lecture classes did not change instructional approaches from year to year, the instructional differences between the primary case and the lecture classes may have also persisted in both years. In addition, the student sample in the primary case and the lecture classes appeared to be drawn from the same population in both years, and there were no significant differences between groups on the pre-test. These three factors were partly controlled in both years indicating that there were some important regularities that were maintained in the year the test was taken, 1999, and the year of the current study.

In order to explain how students from the primary case performed significantly better on the initial test questions designed to measure the process skills of generating hypotheses, describing data, identifying assumptions behind conclusions, and designing experiments (positive pre-post differences $p<0.05$) than students from the lecture 1 and lecture 2 classes, we must examine the factors that distinguished the primary case from the lecture classes.

There were a number of factors that may have produced the difference in the initial test result between the primary case and the lecture classes, and one of those factors may have been instruction. One of the findings of the current study was that I detected a lower frequency of student engagement with some of the fundamental processes of scientific inquiry in the lecture classes compared with the primary case, and I hypothesized in the current study that differences in instruction between the lecture classes and the primary case contributed to differences in student engagement. Given the instructional and statistical regularities between groups from year to year, it was plausible that the GD approach to instruction that was documented in both years in the primary case may have partly produced the higher gains in process skills on the initial test compared with the lecture 1 class that did not implement the GD approach to instruction.

Lecture 2; however, also attempted the GD approach to instruction but the primary case had significantly greater gains than lecture 2 on the initial test. It could be suggested then that there was likely a combination of factors in the primary case that may have influenced student gains on the initial test, including the smaller class size, higher level of student interest in chemistry, small group discussion, student interaction with computers, and teacher use of guidance strategies to facilitate GEM cycles in the primary case, all factors that were not present in the lecture 2 class according to our observations. Therefore, this study was not designed as a controlled experiment which isolated the variable of teaching approach to look for effects of that variable alone. However, in a method of comparative case studies, one can still ask the question, "What is the most viable hypothesis for why the primary case was the only group to show a significant gain in process skills?" Thus, the purpose appropriate to a case study is to generate the most viable hypothesis rather than to test a particular hypothesis.

Best explanation. Thus, in an attempt to best explain the significantly greater gains in the initial test of the primary case compared with the lecture classes in 1999, a viable hypothesis that explains all of the data is that the GD approach to instruction, in combination with other factors, triggered a sustained student engagement with process skills that was not observed in either lecture class, and the sustained student engagement with process skills contributed to the significantly better pre-post course performance on the initial test in the primary case than the lecture classes. Due to statistical regularities between the year the initial test was administered, 1999, and the current study, it is plausible therefore, to suggest that a sustained engagement with these processes over an extended period of time may have contributed to the significantly higher pre-post course gains that emerged on the initial test in the primary case compared with the lecture classes.

Two diagrams on the next two pages conclude this case study by suggesting how, in theory, students within the primary case may have improved their process skills. The second diagram suggests, in theory, how students in the primary case may have improved their process skills significantly more than students in the lecture classes. The evidence to support these hypotheses are stated in the diagrams. GDA represents the guided discovery approach, GS represents guidance strategies, PT represents the primary case teacher, LT1 and LT2 represent the lecture teacher 1 and lecture teacher 2, and S represents students in the diagrams.

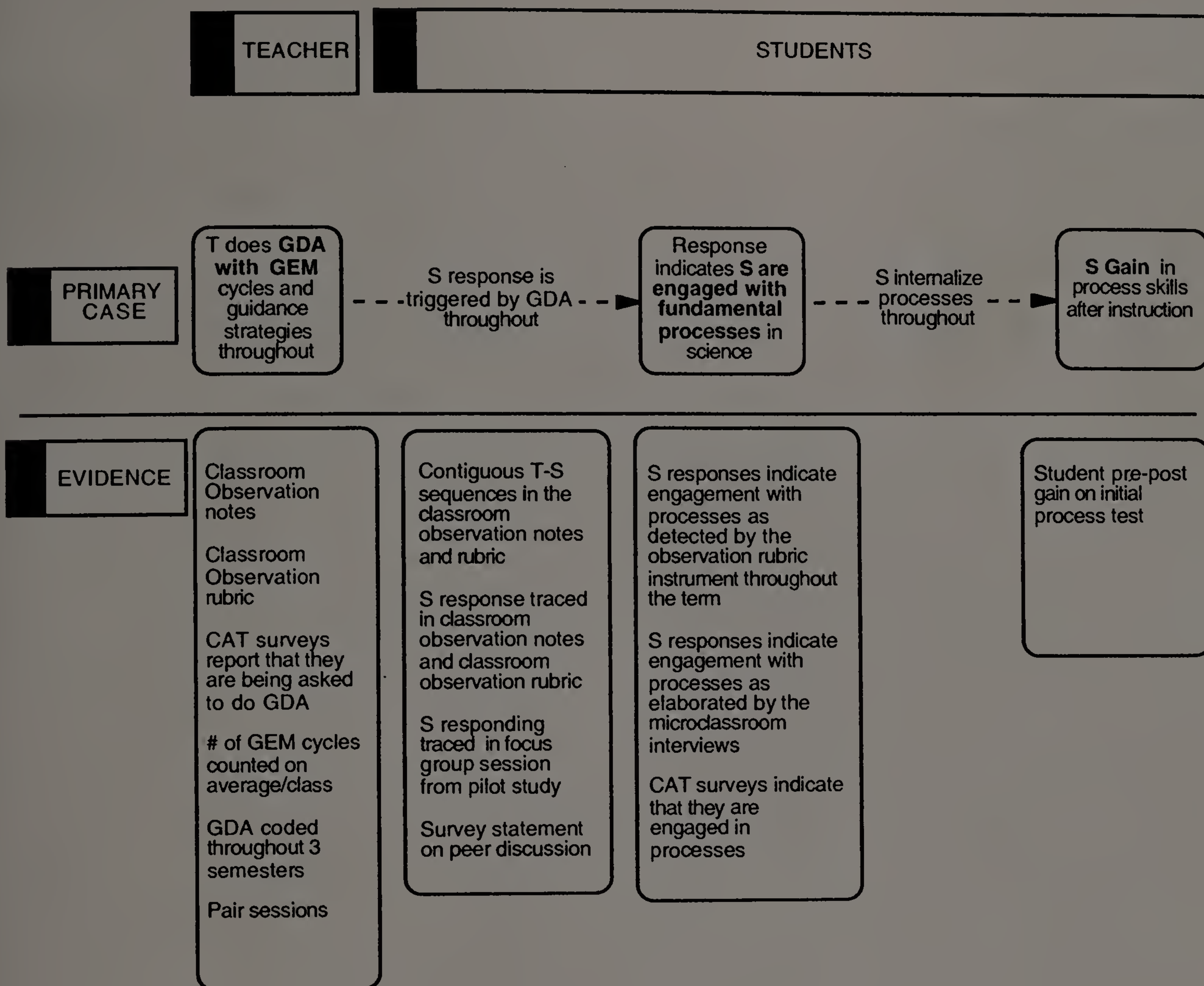

Figure 9. Theoretical diagram of the primary case.

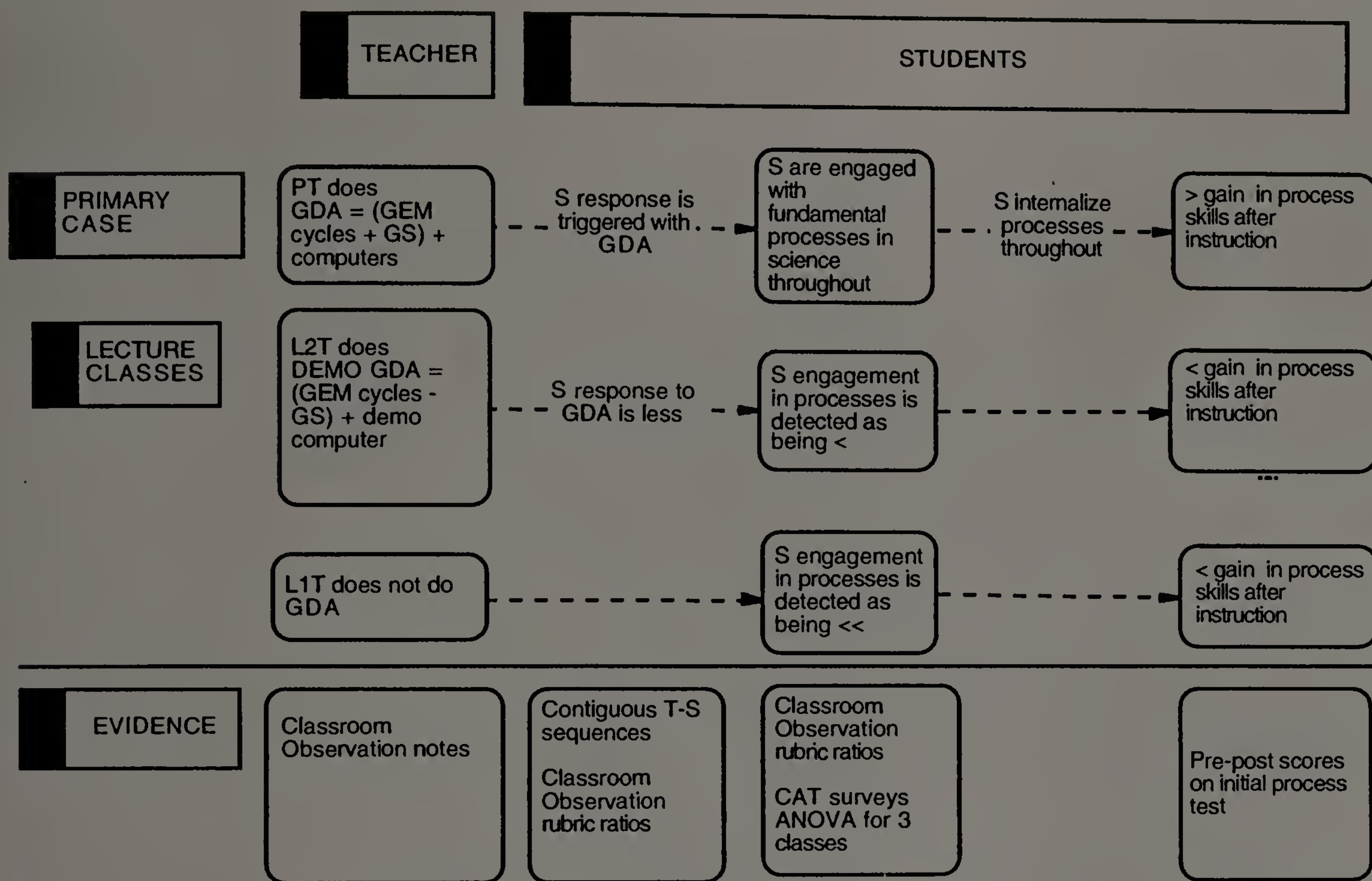

Figure 10. Theoretical diagram of the primary case and the lecture classes.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 Summary of the case study

An initial test of scientific inquiry skills revealed that students enrolled in a computer enhanced introductory chemistry class using a guided discovery approach produced significantly larger gains after class instruction compared with two other introductory chemistry classes at the same institution and three introductory science classes at two other college institutions. The purpose of this study was to analyze the instructional strategy in this class to understand how it may have contributed to gains in inquiry skills. Classroom observations of the computer enhanced guided discovery class, and two other lecture based chemistry classes, uncovered a pattern of instruction in the guided discovery case that was markedly different from the other two classes, yet more similar to model construction processes of scientists. Analysis of classroom observation rubrics and over 300 student CAT surveys confirmed a higher frequency of students' generating ideas about chemistry, constructing explanations, and quantitative problem solving in the guided discovery case than the lecture-based classes, and a higher rate of teacher requests for students to engage in two of these processes. Small group observations revealed students' reasoning processes as they interacted with their teacher and the computer during instruction.

The components of the instructional strategies described in this case study present a fairly extensive and carefully thought out activity and support structure in chemistry. The central pattern of instruction was referred to as the guided discovery (GD) approach and was characterized by generate, evaluate, and modify or GEM cycles, other teacher guidance strategies, and the integration of Chemland interactive computer tools. Six teacher activities were identified that triggered GEM cycles, some of which included asking students to compile information from Chemland, asking students to find the trend in the information, and providing discrepant information. Associated with the teacher activities were fifteen other teacher guidance strategies, including using analogies, extreme cases, comparisons, incremental values, work back from the data, design a new test, what is wrong, why, think of an individual molecule, gather more information, see if this holds true, and test new variables. The teacher and the students worked with Chemland to select and constrain variables, produce data quickly, dynamically regenerate graphs, push values to the extreme, pause and proceed in increments, and visualize multiple, color coded representations.

The classroom observations, classroom observation rubrics, CAT surveys, and in-depth pair sessions detected that the GD approach to instruction was triggering responses from students, and the responses seemed to indicate that the students in the primary case were engaged with several fundamental and complex processes associated with scientific inquiry. These processes included students generating multivariate relationships between two variables, evaluating the empirical consistency of the relationships in chemistry, quantitative problem solving, and constructing causal explanations, to name a few. Analysis of the primary case revealed also that these processes were sustained throughout the semester, without compromising content coverage in introductory chemistry.

In contrast, two other introductory chemistry classes were also examined (lecture 1 and lecture 2). Although both primary case and lecture teachers shared the same syllabus and reported similar content and process goals for their students, the method of instruction in the lecture 1 class was markedly different. A linear pattern of instruction emerged from classroom observations of the lecture 1 instructor where the instructor consistently introduced a term at the start of class, then conducted a classroom demonstration or described relevant examples, and, if there was time remaining, modeled how to solve a chemistry problem. The approach to instruction in lecture 1 was observably different from the teaching strategies that characterized the GD approach to instruction in the primary case because there was limited evidence of the lecture 1 instructor asking students to generate relationships, evaluate and modify them in light of new information. In this regard, the activities in the primary case could be considered distinctive compared with the more traditional approach to instruction that was represented by lecture 1.

On the other hand, the approach to instruction in lecture 2 was similar to the primary case. Many of the same teacher activities in the primary case were observed with similar frequencies as in the lecture 2 class; however, the frequency of student responses to these activities was measurably lower in the lecture 2 class than student responses to these activities in the primary case. This finding indicated that even though the GD approach to instruction was attempted in lecture 2, lecture 2 produced a lower level of student engagement with these processes compared with the primary case. The lower frequency of student responses in lecture 2 may have been caused by a number of factors that distinguished this class from the primary case, including the larger size of the lecture 2 class, lower level of student interest in chemistry in lecture 2, the absence of small group discussion as a mode of interaction in lecture 2, and the use of a single demonstration computer in lecture 2 as opposed to multiple computers in the primary case. But it was also discovered that the lecture 2 instructor provided 40% of the answers for questions initially asked to the students, much more than in the primary case, and some of which may have otherwise launched student inquiries that generated ideas in chemistry and constructed explanations as they had done in the primary case.

This finding highlights the need for explicit guidance strategies for teachers when student answers were apparently not forthcoming. Guidance strategies were noticeably absent in lecture 2's instruction. Therefore, a recommendation suggested to lecture 2 was to couple teacher activity structures with the guidance strategies in an attempt to trigger student responses and amplify frequencies of student engagement with the fundamental processes of science .

Contrasting the cases led one to believe that the GD approach to instruction was a distinctive approach to instruction compared with the more traditional approach that was represented by lecture 1. Contrasting the primary case with lecture 2 further suggested that such instructional methods can be transferred, in part, to a large lecture setting. Finally, it was hypothesized from contrasting the cases that it was probably a combination of factors that contributed to successful student engagement with several of the fundamental processes of science in the primary case, including the use of specific teacher guidance strategies to amplify student responses.

Thus, the primary case appeared to produce persistent engagement with several of the fundamental processes of scientific inquiry over an extended period of time compared with the more traditional methods of instruction in chemistry that were observed. The evidence presented in the case study further suggested that the strategies in the GD approach were important in developing students' process skills and may suggest a promising initial model for inquiry instruction by chemistry teachers.

5.2 Main recommendations for teachers

Four categories of recommendations for teachers who may be interested in this approach to inquiry were drawn from the case study of the primary case and the lecture classes. These categories are listed first below and developed in the following sections.

1. Contrasting the primary case with lecture 2 led one to believe that teacher guidance strategies played a critical role in amplifying student engagement with processes in the primary case. Fifteen guidance strategies were reported in the case study and are

recommended for teachers who wish to encourage students to be engaged with similar processes in the classroom.

2. Students worked with a suite of interactive computer modules called Chemland in this study. Working with the interactive computer tools may have had some implications for facilitating student processes. The computer affordances were hypothesized with implications for computer use.

3. Based on observations of lecture 2, I was able to suggest several recommendations designed to adapt the GD approach to the large lecture theater.

4. Recommendations to enhance student ownership, process skills, and understanding of the nature of scientific inquiry are suggested, in addition to suggestions for formative assessment.

Specific teacher guidance strategies may play a critical role in the GD approach to instruction. Although both the primary case and lecture 2 implemented the GD approach to instruction, a lower frequency of student responses to instruction were observed in lecture 2. Upon examination of instruction in lecture 2 it was also discovered that the lecture 2 instructor provided 40% of the answers for questions initially asked to the students, some of which may have otherwise launched student inquiries into generating ideas in chemistry and constructing explanations as they had done in the primary case. This finding highlights the need for explicit guidance strategies for teachers when student answers do not appear to be forthcoming. Guidance strategies were noticeably absent in lecture 2's approach to instruction, and were observed in the primary case, leading us to believe that teacher guidance strategies may have played a critical role in amplifying student engagement with processes.

Based on classroom observation notes and the in-depth pair sessions, the case study produced explicit descriptions of 15 different teacher guidance strategies to support student inquiry. The guidance strategies included using analogies, extreme cases, comparisons, incremental values, work back from the data, design a new test, what is wrong, why, think of an individual molecule, gather more information, see if this holds true, and test new variables.

Computer affordances. The full integration of interactive computer tools was observed throughout the primary case. The interactive computer tools were not designed as a substitute for the teacher, but as a source of information that was available efficiently and dynamically to the students. Students could interact with the software by selecting and manipulating relevant variables such as the temperature of the system, the concentration of substances, or the charge on ions. The output showed changes to the system, dynamically representing them in multiple ways such as in the form of a graph and/or an animation.

I observed students generating large amounts of information quickly with Chemland. I also observed students selecting and reselecting variables, dynamically regenerating graphs, comparing color coded curves on the graph or color coded animations, changing variables in increments or to extremes, and viewing multiple representations of molecules or lab results. Although such a comparison was not the focus of this study, I would make a confident conjecture that students were able to do these processes much faster than they would be able to in a wet lab. These activities with Chemland may have had implications for the number of cycles of pattern generation and evaluation of the consistency of relationships that they were able to go through in the GD approach to instruction.

Adapting the GD approach to instruction in the large lecture theater. Contrasting the primary case with lecture 2 suggested that GD methods can be transferred, in part, to a large lecture setting; however, there were several emergent issues that were raised when this approach was implemented in lecture 2. These issues concerned: attempting small group discussion in the large lecture setting; working with a single computer in the large lecture setting; and what to do when students are not responding in the large lecture setting.

Small group discussion in the large lecture setting. Small group discussion has been linked with positive effects for student participation and achievement, even when technology is involved (Lou et. al., 2001), and examples of small group discussion have been documented in large lectures (Yuretich & Khan, et. al, 2001; Khan & Clement, 2000; Khan & Clement, 1999); however, small group discussion was not observed in lecture 2. Small group discussion may be a strategy that could improve student participation in the large lecture setting, thereby contributing to a higher level of student engagement with the activities in the large lecture.

Working with a demonstration computer in the large lecture setting. The instructor in lecture 2 had a single computer at the front of the classroom, but was able to integrate Chemland interactive computer tools throughout the semester. I observed the instructor in lecture 2 demonstrating the software on a large screen at the front of the classroom. The lecture 2 instructor asked students to suggest changes to the parameters in the simulations, and asked students what the outputs suggested about relationships between two variables. The instructor worked in this demonstration mode throughout the semester, suggesting a viable strategy for other instructors who must work with a single computer in their classrooms.

When the students are not responding in the large lecture setting. A lower level of student engagement in the GD approach to instruction was detected in the lecture 2 setting than the primary case. I observed the teacher asking and answering his own questions, possibly short-circuiting student engagement with the GD approach to instruction. Furthermore, I observed that the lecture 2 instructor did not employ guidance strategies when student answers were not forthcoming. These instructional differences may have contributed, in part, to the finding that the lecture 2 students were not engaged with the GD approach as much as students in the primary case. Fortunately, the instructional differences between the implementation of the GD approach in the lecture 2 class compared with the GD approach in the primary case did not represent major departures from instruction. Therefore, one of the recommendations suggested to lecture 2 was to couple teacher activity structures with more specific guidance strategies when student answers do not appear to be forthcoming in the large lecture setting in an attempt to trigger student responses and amplify the frequencies of student engagement with the fundamental processes of science.

5.3 Other recommendations for teachers

The recommendations that follow are based on criticisms of the GD approach in the primary case. The recommendations are designed for instructors who are interested in adapting the GD approach to their science classrooms, but may also be interested in enhancing student ownership of inquiry, student engagement with other processes associated with inquiry, understanding of the nature of science, and formative assessment.

Student ownership. There was no student evidence of generating inquiry questions in the GD approach to instruction that I observed in the primary case or in lecture 2; rather, the teacher generated the questions for inquiry. Many teachers, however, have an interest in student ownership of inquiry. To move the GD approach to instruction in that direction, I recommend that teachers could attempt to fade scaffolding as students' skills progress, so that students are encouraged to eventually generate their own questions for inquiry and spontaneously construct explanations and evaluate relationships.

Enhancing the GD approach to instruction with additional processes associated with scientific inquiry. There was limited evidence of students engagement with several other processes commonly associated with inquiry, such as: making predictions, comparing theoretical frameworks, reading primary literature, communicating in science with presentations, or conducting statistical analyses of data in the primary case. These processes were not observed being triggered by the GD approach to instruction.

Thus, I recommend that teachers who are interested in enhancing the GD approach to instruction to consider for example, asking students to compile information from primary literature, asking students to make predictions before generating relationships during the generation phase of instruction, and asking students to conduct statistical analyses of the data and graphs during the evaluation phase.

Understanding the nature of scientific inquiry. One of the goals of the primary case teacher was to encourage students to understand how scientists approach exploration and where they get the concepts from, "I want them to learn chemistry, [but] I don't want them to just understand the concepts--I want them to understand where to get the concepts and where they come from" (Khan, 2000).

In a faculty interview, the primary case teacher elaborated on this view,

> [A]side from getting them good at chemistry, [my goal is also] getting them good, in a general sense, of how to approach exploration. I don't want to say approach problems cause that makes it sound like approaching math problems or problems from the book. But more a matter of getting them [to have] a good feel for how it is people go and find information, then from that information figure [out] what we know scientifically. So that is one of the other main goals because that is something that they don't really get anywhere else.

In order to encourage students to understand the nature of scientific inquiry, the primary case teacher had students explore in a way that was similar to scientists' exploration:

> And the way we do that is to, instead of presenting them with conclusions, facts, relationships in chemistry were they can say, 'oh yeah, I kind of see that relationship', and tune out, what we do instead is we give them information, the data of one sort or another, and ask them to figure things out from it. And what they end up figuring out from it is the relationship we want them to know. And so what they get from that is they get the exploration part because they are doing the exploring, using this information and coming up with these conclusions, plus they're getting a much deeper understanding of the areas of chemistry we want them know. And they don't really realize that is what they are doing for the most part until they get there.

For teacher's who are interested in further developing students' understanding of the nature of scientific inquiry, an explicit discussion of the nature of scientific inquiry or reflection exercises may encourage students to realize in what ways what they are doing with the GD approach to instruction is similar and what ways it is not similar to scientific inquiry.

Although the majority of students in the primary case that were surveyed (n=22) agreed to the CAT post-survey statement, "I understand how scientists assess and modify theories about unobservable processes" at the end of the course, the primary case teacher acknowledged that helping students to develop an understanding of the nature of scientific inquiry is problematic:

> [O]ne main danger that's part of the whole idea of running a class that way is that it gives them the idea that's how scientists explore. The one danger, it's a both a good thing and a danger, is that is how the scientific *community* explores is a better way of putting it. Because individual scientists, they have to do a ton of work to get 5 of these little data points, that students, in a matter of ten minutes, will use 50 of. So in a class period, they can go through peoples' year's worth of work in terms of obtaining the data in the first place to then putting that all together and then drawing these conclusions. So what happens is we are bypassing a whole bunch of work to get the students to be in a position that the scientific community overall is in--to look at a whole bunch of information and put it all together to come up with a general concept. The kind of thing that gets into a textbook. And the danger is that they will come away thinking it's that easy! That science works by, you go and you get these 50 [data] points, and you take these 50 points and you come up with this relationship, and you know it ends up in a textbook. With an individual person it's very, very hard for them to make that kind of contribution in anything close to that in a reasonable amount of time. So we tell them that, 'By the way you know the experiments, to do this it would take you 3 weeks to get this data point.' We tell them that along the way, but it's the kind of thing they don't really get a gut feel for until they actually go and do real lab work. Real research like type lab work. Even doing lab work as part of the class doesn't really solve that problem.

Thus, for teachers who are interested in helping students further develop an understanding of the nature of scientific inquiry as they are engaged in the GD approach to instruction within the classroom, I recommend encouraging explicit discussions of the process and reflection exercises on student activities.

Formative assessment. For teachers who are interested in the formative assessment of process skills and conceptual understanding as the semester progresses, I recommend spot checks. For example, the primary case teacher polled students on the viability of hypotheses or the use of OWL, an electronic homework system, that administered multiple choice questions on basic chemistry and provided quick feedback to the teacher. [I also recommend the regular inclusion of open ended, short answer transfer test questions at the conclusion of a lesson as one method of gauging student progress. These forms of assessment may release valuable information about students' progress during course instruction.

5.4 Significance of the research

The lists outlined here suggests several potential contributions of the current study to research methodology and educational practice.

Implications for research methodology

1. A "method of contrasting cases" was employed in this study where a primary case was compared with two other classrooms. The inclusion of the two other classrooms, lecture 1 and lecture 2, in the study was not intended to serve as a controlled comparison to the primary case; rather, the purpose of including descriptions of lecture 1 and lecture 2's approaches to instruction was as an attempt to acquire initial data on the question of whether the primary case teacher's methods departed in a significant way from the normal teaching methods used in the chemistry department. The contrasting cases method was useful because it provided preliminary evidence on which dimensions of instruction were unique. Contrasting cases also allowed us to expand the recommendations for teachers to two different classroom environments, the primary case setting and the lecture classes setting. Finally, the contrasting case method provided initial contrasts that could be used to stimulate the design of later studies with larger samples.

2. In order to unpack the instructor-student interactions it was necessary to develop a finer grained set of concepts and language for describing the learning processes involved in model construction, and for the different strategies used to foster them.

Qualitative case studies of instructional interactions to identify key issues, concepts and variables were therefore an important and appropriate foundation for the project. But the study also included quantitative measures as key variables were identified and coding or issue based surveys became possible and appropriate (Clement, 2000). Thus the study used a mix of qualitative and quantitative methods.

3. Peer discussion at the computer and discussion with the teacher was documented during the classroom observations; however, the interaction between the student, the teacher, and the computer was difficult to capture in great detail in the class of a typically dynamic classroom period. The purpose of the "in-depth pair sessions" was to capture and elaborate on students' responses to teacher interventions and their learning trajectories in greater detail than the classroom observations would allow. A special interview protocol was designed to document students' learning pathways during instruction with the computer (Khan, 2001).

In these in-depth sessions, the teacher "taught a class" to a pair of students, where the teacher, the students, and the interactive computer tools played the same roles that were observed during class, except students were prompted by an interviewer to "think out loud". This approach to interviewing with computers yielded rich information about students learning trajectories as they were engaged with the teacher and interacting with the computer. The outcomes of this approach were detailed documentation of students' learning pathways and processes and explicit descriptive examples of the teachers behaviors that supported student learning.

4. Model based learning theory with a case study method is a framework that allows one to trace the effect of innovative teaching strategies on classroom student processes and post course outcomes (Clement, 2002).

5. Keys and Bryan (2001) suggested that practicing teachers offer perspectives on teaching and learning that were not available even from extended observational studies of and by researchers. Thus, they recommended that more research was needed on teacher-designed approaches to inquiry-based instruction, as well as teacher-designed adaptations of curriculum to their own unique situations. This research describes a study of teacher-designed approaches to inquiry based instruction (the primary case), and teacher-designed adaptations of curriculum to their own unique situations (lecture 2 class). The contrasting case methodology used to examine teacher-designed approaches to inquiry may be applicable to other classroom based research.

Implications for practice.

1. Often in science classrooms, the development of process skills, if handled at all, is relegated to the lab or homework assignments, and the focus of classroom time is driven solely by content goals; this study described how the teacher modeled a guided discovery approach that engaged students in several fundamental processes associated with scientific inquiry within the college classroom. The instructional implications were that if scientific inquiry could be practiced with some success in the college classroom, it may offer multiple opportunities to unify the goals of attaining content and process skills. This congruency may reduce a common complaint about the disparity between what is taught in the class and what is investigated in the lab.

2. In contrast to using complex simulation software and microworlds that attempt to scaffold inquiry extensively with libraries, tools, expert feedback, and simulated lab or field environment programmed in complex algorithms (Soloway, et al., 1997); this study describes a way teachers could encourage

the development of inquiry skills with downloads of compact simulations that were readily available on the Internet. Teachers may find this an encouraging first step to the integration of simulations into their instruction.

3. A trend in many current software projects is to program expert coaching into the "computer" (Acovelli & Gamble, 1997) and assign a less active role to the instructor. This study highlights how a chemistry teacher and groups of students in small groups could play active roles in a computer based classroom, and the importance of their interaction in the development of inquiry skills.

4. With curriculum standards recommending that students must "arrive at the *essential content* of science and technology through *inquiry*" (Massachusetts Science and Technology Curriculum Framework, 1997), teachers are now calling for more prescriptive measures of inquiry based teaching methods necessary to achieve this standard (Keys & Bryan, 2001). This study, provides rich descriptions of how to do both with carefully thought out teacher activity structures and specific guidance strategies of a successful inquiry based chemistry class. By elaborating on the instructional strategies of the teacher to facilitate inquiry in this classroom, a promising initial model for inquiry based instruction in chemistry has emerged for science teachers who are interested in implementing explicit instructional strategies for inquiry without compromising content.

5. Historically, chemistry has long been considered one of the most difficult of the sciences in which to enhance student performance (Shymansky, 1983), so we are still searching for good ways to teach chemistry. The focus of this study is a distinctive chemistry classroom, where students emerge with positive gains in process skills. The

central pattern observed in this classroom was generating relationships between two variables, evaluating the consistency of those relationships in light of new information, and modifying those relationships in chemistry, or GEM cycles. We have evidence that suggests that GEM cycles foster student engagement with the fundamental processes of science in this chemistry classroom, plausibly contributing to pre-post course improvements in students' process skills. These early findings suggest that teaching with GEM has the potential to enhance student performance in chemistry, a historically difficult subject in which to strengthen student performance.

6. The contrast between GD instruction in the small electronic classroom (the primary case), and GD instruction in a large lecture theater with only a single computer (lecture 2), afforded important insights in scaling up this approach to instruction for a larger group of students. Recommendations include using a single computer in demonstration mode, organizing small group discussion modes, and employing teacher guidance strategies to encourage whole classroom participation in larger classroom settings.

7. Even though the GD approach to instruction was observed to be relatively successful at engaging students in the fundamental processes of science throughout the semester in introductory chemistry at this department, one of the concerns of implementing such an approach to instruction is that teachers would not be able to simultaneously cover the necessary content outlined in the course's syllabus. In addition to engaging students in several of the fundamental processes in science, the primary case teacher was able to fulfill the content goals for the course.

8. We have evidence that student engagement with fundamental processes of science were sustained throughout the semester, spanning 11 different topics in introductory chemistry. This suggests that the GD approach to instruction is a general framework that, perhaps in combination with other factors, is sustainable throughout an entire course.

5.5 Future directions

There are several possible extensions of the current study.

1. Initial findings on the in-depth pair session tests for conceptual understanding in chemistry reveal significant pre-post gains by individual participants on the test after instruction ($n=12$, $p<0.01$). While these findings represent a very small sample size, it may be that the guided discovery approach described fosters deeper learning of content. This suggests comparing an experimental group with a control group on content gains if an appropriate control group can be found.

A possible extension of this work could include an investigation of conceptual model construction. Additional qualitative analysis of the in-depth interviews may provide insights into how students are constructing models of processes such as evaporation and boiling.

2. There is an interest in developing possible scripts for the independent use of the computer simulations outside of class. The identification of teacher activities and teacher guidance strategies associated with the GD approach to instruction in the current study may provide several scripts that could guide students to work with the simulations more independently.

3. Several teachers have expressed a desire to apply the GD approach to instruction to their science classrooms. This interest in the GD approach to instruction suggests a need for professional development. In the past, professional development occurred in a peer supervision model where the primary case teacher co-taught the class with new faculty. Case based and video based professional development activities may support teachers who are interested in professional development but may not be able to co-teach the class with the primary case teacher.

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